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Laboratory Evaluation of Expedient Low-Temperature Admixtures for Runway Craters in Cold Weather

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Laboratory Evaluation of Expedient Low-Temperature Admixtures for Runway Craters in Cold Weather

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Abstract

The research included in this report investigates admixtures that can improve the low-temperature early strength gain performance of two products already in existence (which are currently in limited use by the Air Force) for hasty runway repair. The first product, a "flowable fill," is a low-level cementitious sandy mixture used to rapidly fill the bulk of a runway crater; the second product, a rapid setting concrete, seals the final 10–12 in. of the crater and allows heavy-vehicle trafficability.

The primary operational requirements, which the current two-part solution meet at higher temperatures (greater than 10°C) but which require improvements at lower temperatures (−10°C to 10°C), involve time of set and 2 hr unconfined compressive strength (UCS). This research ignores typical concerns, such as long-term durability, aesthetics, and corrosion, that are of minimal importance in this expedient field-use application—horizontal surface repairs not expected to last more than two to five years. Results from this study are expected to be incorporated into operational testing, using Air Force equipment, personnel, and techniques, for small and large crater repair at sub-freezing temperatures. This report describes laboratory tests to improve the early strength gain performance of both repair materials to repair small-to-large craters at ambient temperatures of −10°C to 10°C.

Contents

Illustrations

Figures

Tables

Preface

This work was funded by the Air Force Civil Engineering Center (AFCEC) under the Airfield Damage Repair Modernization Program (sponsor: Dr. Craig Rutland) at the U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL), to answer questions related to improving cold weather performance of materials used in expedient horizontal surface repairs.

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Acronyms and Abbreviations

ADR	Airfield Damage Repair
AFCEC	Air Force Civil Engineer Center
AIC	Aikake Information Criterion
Al	Aluminum
$Al_2(SO_4)_3$	Aluminum Sulfate Hydrate (or Aluminum Sulfate)
Al_2O_3	Aluminum Oxide
AS	Aluminum Sulfate (Hydrate)
ASTM	American Society for Testing and Materials
BIC	Bayesian Information Criterion
C_2S	Dicalcium Silicate, or Larnite
C_3A	Tricalcium Aluminate
C_3S	Tricalcium Silicate
C_4AF	Tetracalcium Alumino Ferrite
$CaCl_2$	Calcium Chloride
$Ca(NO_3)_2$	Calcium Nitrate
CaO	Calcium Oxide
$CaSO_4$	Calcium Sulfate
CC	Calcium Chloride
CERL	Construction Engineering Research Laboratory
CLSM	Flow Consistency of Controlled Low Strength Material
CN	Calcium Nitrate
COTS	Commercial Off-the-Shelf
CRREL	Cold Regions Research and Engineering Laboratory
CS	Calcium Sulfate (Hemi-Hydrate)

CSA	Calcium Sulfoaluminate
ERDC	US Army Engineer Research and Development Center
Fe_2O_3	Iron Oxide
FTIR	Fourier Transform Infrared
Gle	Glenium 7500 Water Reducer
GSL	Geotechnical and Structures Laboratory
H_2O	Water
IR	Infrared
LOI	Loss On Ignition
MRE	Meal, Ready-to-Eat
OH	Hydroxide
Poz	Pozzutec 20+ Accelerator
RCC	Roller-Compacted Concrete
RMSE	Root Mean Squared Error
SEM	Scanning Electron Microsopy
Si	Silicon
SiO_2	Silicon Dioxide
SN	Sodium Nitrate
SS	Sodium Sulfate
SO_3	Sulfur Trioxide
Sug	Cane Sugar
TGA	Thermogravimetry Analysis
UCS	Unconfined Compressive Strength
USACE	US Army Corps of Engineers
w/c	Water-Cement
XRD	X-ray Diffraction
XRF	X-ray Fluorescence Spectroscopy

Unit Conversion Factors

Multiply	By	To Obtain
bars	100	kilopascals
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
ounces (U.S. fluid)	2.957353 E-05	cubic meters
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
square inches	6.4516 E-04	square meters
yards	0.9144	meters

1 Introduction

1.1 Background

In support of the U.S. Air Force Civil Engineer Center's (AFCEC) Airfield Damage Repair (ADR) Modernization Program, the Engineering Research and Development Center (ERDC) Geotechnical and Structures Laboratory (GSL) Airfields and Pavements Branch previously developed a novel solution to the problem of rapidly repairing, in all environments, small and large craters on airfields. Building on this solution, our report investigates admixtures that can improve the low-temperature early strength gain performance of two products developed for the Airfield Damage Repair Modernization Program for the purpose of expedient runway repair: a Utility Fill for rapid bulk crater filling and a Rapid Set concrete for heavy-load trafficking and load support.

The solutions hereby provided are intended for only the stated purpose: the expedient filling of blast holes (in horizontal surfaces at −10°C to 10°C) using GSL's Utility Fill and Rapid Set hard cap solution approach when low temperatures are a concern (high altitude, winter, or other expectation of near- or below-zero temperatures). These solutions are not intended for civilian construction because the material produced may not meet the required quality, durability, and appearance normally required by most horizontal and vertical construction applications.

1.2 Project description

The ERDC-GSL runways and airfields program's novel solution to airfield crater repair can be applied in all environments, in a wide range of temperatures. The Air Force's expedient ADR process occurs in two steps: first, filling the bulk of the crater void space (less 10 in. to the top of the crater) with a rapidly hardening flowable fill material called "Utility-Fill One-Step" (produced by Buzzi Unicem USA Inc). The Utility Fill is a dry, gray powder composed of silica sand and a variety of calcium silicates, aluminous materials, and gypsum, hardening quickly to an initial "set" of approximately 250 psi with the on-site addition and minimal mixing of water (a volumetric mixer is preferred due to rapid-set properties). Once initial set has been reached (typically about 30 min), a second layer, called the “hard cap” is added to the crater (filling the final 10 in. depth) to increase the strength and durability of the road surface. The hard cap consists of a slight variation of the commercially available “Rapid Set Concrete Mix” (produced by CTS, cement specifically for the GSL program). The Rapid Set mix also requires only the addition of water and mixing because it consists of a pre-blend of Type III Portland cement (calcium sulfoaluminate [CSA] cement with some small amount of admixtures for workability), 3/8 in. pea gravel, and a small amount of concrete sand (less than 1%). The hard cap is designed to have an initial workability, a set (500 psi) by 45 min from the initial addition of water, and an unconstrained compressive strength (UCS) at two hr that will allow for the minimum of 100 (and target 1000+) vehicle traffic loads required by the Air Force. The Air Force minimum loading is simulated during testing using GSL’s load cart and an F-15 tire loaded at 35,000 lb at 325 psi.*

While the two-step solution to crater repair has demonstrated success at mild temperatures (greater than 10°C), both the Utility Fill and the hard cap demonstrate issues with time of set (and with the ability to set and not freeze) and early strength gain in temperature ranges of –10°C to 10°C. In an attempt to improve the two-step solution’s performance and reliability over a wider temperature range, the research requirements outlined below address this deficiency. In addition, to target other potential horizontal surface repair applications, including asphalt surface and sub-surface expedient repair, our research explored improvements to the Utility Fill at near- and sub-freezing temperatures.

ERDC tested and evaluated a variety of methods to improve the performance of the existing Utility Fill and hard cap over the widest feasible low temperature ranges with minimal alteration to candidate solutions at different temperature ranges. This investigation used a combination of rapid materials analyses and a survey of the most promising materials outlined in previous cold-weather admixtures research to perform a down-selection of potentially suitable admixtures (see Section 3). For expediency, some admixtures were initially screened for suitability using mortar mixes by using primarily ASTM (American Society for Testing and Materials) pene-

* For more information on similar crater repair methods, equipment, and materials used by the U.S. Army, see Center for Army Lessons Learned (2011).

tration resistance procedure C403 (ASTM International 2008b). We tested with a concrete mix the best performing combination, performing both penetration resistance and unconfined compressive strength testing. All laboratory tests were conducted at the ERDC Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH. In addition, a variety of materials analyses were conducted at ERDC-GSL in Vicksburg, MS, and at the ERDC Construction Engineering Research Laboratory (CERL) in Champaign, IL.

1.3 Project objectives

The GSL program manager outlined three areas (discussed in the sections below) of research involving improvements to the set times and early strength gains for both the Utility Fill and Rapid Set materials.

1.3.1 Admixture investigations

The first goal was to determine a suitable admixture and proportion necessary to improve the performance of the Utility Fill under the following constraints:

1. Utility Fill time of set (time to reach ≥250 psi penetration resistance) minimum and maximum: 15 min and 30 min.
2. Temperature ranges suitability goal for new admixture: −15°C to 10°C.
3. Admixtures must be added to the water with no alterations to the Utility Fill dry mix.

To investigate possible admixtures for addition to the Utility Fill mix, implied tasks included evaluating the chemistry of the flowable fill, identifying candidate admixtures for inclusion, running lab tests (small batch), and performing other investigations and analyses.

In addition to investigations involving the addition of the admixture to the Utility Fill, we were to determine a suitable admixture and proportion necessary to improve the performance of the Rapid Set under the following constraints:

1. Hard cap time of set (time to reach 500 psi penetration resistance) minimum and maximum: 15 min and 45 min.
2. Temperature ranges suitability goal for new admixture: −15°C to 10°C.

3. 2 hr UCS: ≥2500 psi.
4. Admixtures must be added to the water with no alterations to the Rapid Set dry mix.
5. Mixing water temperature is 5°C to 10°C.

Note that using only aluminum sulfate hydrate ($Al_2[SO_4]_3 \times 12H_2O$) admixture, solutions satisfying the optional fifth constraint would provide an improvement to the performance of the hard cap at cold temperatures because aluminum sulfate acts primarily as an accelerant to the hydration process and is a poor freezing-point depressant. An aluminum sulfate–water solution that remained close to 0°C for an extended period of time would exhibit significant icing and would not have a strong hydration accelerant effect when introduced to the Rapid Set dry mix.

1.3.2 Utility Fill and Rapid Set hot water testing

To improve the initiation of the reaction process (reliability and speed) at low ambient and ground temperatures (−10°C to 10°C) for both the Utility Fill and in the hard cap, the second goal was to determine a suitable admixture and proportion necessary to chemically heat (via exothermic reaction) the mixing water for use in both. Any admixture added must provide this reaction initiation improvement without degrading the performance of either mixture (e.g., set or UCS values or estimates for short-term durability).

This task attempted to satisfy the same constraints as outlined in the first task but in a way that did not alter either mixture (Utility Fill or Rapid Set), instead introducing admixture to the water directly. This approach was perceived by the project manager and client (Air Force) as the ideal solution given the tactical and practical short-term constraints involved in introducing any changes to the mixtures already procured and in use.

A second objective of the hot water testing was posed in the event that chemical heating of the mixing water proved unreliable or ineffective: to improve the initiation of the reaction process (reliability and speed) in both Utility Fill and the hard cap at low ambient and ground temperatures (−15°C to 10°C) and to determine suitable temperatures (to be heated mechanically) of the mixing water.

1.3.3 Aluminum sulfate Rapid Set testing

In previous research, the GSL program identified aluminum sulfate as the best known admixture to add to the hard cap to improve the initial set and 2 hr UCS at temperatures below 10°C. Therefore, our third goal involved quantifying (with a higher degree of statistical certainty than provided in previous GSL testing) the proportions of aluminum sulfate (from the current vendor, Fisher Scientific) necessary to meet the following constraints:

1. Hard cap time of set (time to reach 500 psi penetration resistance) minimum and maximum: 15 min and 45 min.
2. Temperature ranges suitability goal for new admixture: −15°C to 10°C.
3. 2 hr UCS: ≥2500 psi.
4. Admixtures must be added to the water with no alterations to the Rapid Set dry mix.

2 Technical Approach

2.1 Introduction

The desired end state of the materials analyses and laboratory testing was to determine the most reliable method to improve the performance of both the Utility Fill and Rapid Set materials at near- and sub-freezing temperatures where successful performance involved time of set and early strength gain requirements. To reach this end state, testing followed several distinct phases. First, because previous testing identified aluminum sulfate as the most promising admixture for use in the Rapid Set at near and sub-freezing temperatures, the aluminum sulfate Rapid Set test phase was conducted first to better quantify the proportions and effects of aluminum sulfate given a variety of effects variables (e.g., ambient and materials temperatures and water-cement ratio [w/c]).

We conducted two analysis categories in parallel to prepare for the final two test phases. To develop an exhaustive list of admixtures that could allow the Utility Fill and the Rapid Set to meet the objectives in the final two test phases, we conducted a historical analysis of cold-weather concrete and flowable fill materials. Next, we completed a materials and chemistry analysis of both the Utility Fill and the Rapid Set to understand the unique hydration processes occurring in each material and their response to various effects variables. We then combined this analysis with the historical analysis to identify a shortlist of potential admixtures for use in the final two test phases.

After the historical, materials, and chemistry analyses were complete, we began the hot water test phase to determine the feasibility of mechanical or chemical heating of the mixing water to reach the objectives for set time and 2 hr UCS for the Utility Fill and Rapid Set materials. The final test phase explored admixtures (alone and in combination) for their potential based on historical analysis and compatibility with the Utility Fill and Rapid Set materials. To reduce the combinatorial complexity of this test phase, we first determined the effects of individual admixtures, quantifying their effects at minimum and maximum useful proportions. The team determined these extremes by considering historical research and recommendations, water solubility as a function of temperature, and other variables.

After this individual admixtures test phase, we used the admixtures in combination to obtain the material performance results historically required as will be discussed in further detail in the Section 3 *Summary of Related Historical Research* (freeze point depressant, acceleration of the hydration process, and potential initial retarders to lower results variability).

To further reduce the time required to perform a large number of tests during the admixture investigations phase, we sieved the Rapid Set materials and removed all course aggregates, performing all testing with the remaining mortar (cement, sand, mixing water, and admixture). While we did not expect the set times and strength gains for the mortar mixes to minimally deviate from concrete mixes with the same admixture ratios, this procedure allowed for a more rapid screening of poor combinations of admixtures by ruling out candidates. Previous testing (for example, Oren et al. 2013) demonstrated the suitability of mortar testing as a surrogate for concrete batch testing if the results of the mortar testing is suitably mapped to equivalent concrete batches with similar effects variables and proportions (e.g., ambient and materials temperature, w/c, and admixture proportions).

2.2 Materials normalization

The team used the following procedure to prepare the Utility Fill and the Rapid Set materials for all testing. Both materials were provided directly from the manufacturer and from a stockpile from previous testing (at GSL). Therefore, due to potential settling of the component materials in the stock pile, the materials exhibited a larger degree of variability in component proportions than if delivered from the manufacturer in 60 lb buckets. Typical testing allows for tight controls of the ratios of cement to fines to course aggregates ratios; but for two primary reasons, determining these exact ratios and controlling them to typical laboratory testing standards was infeasible in this rapid investigation. First, the exact proportions (and their variability in each batch) and material contents are proprietary information and so must be experimentally determined. However, experimentally determining these proportions with a large degree of precision was infeasible because the materials used were harvested from 2000 lb “super sacks” from the manufacturer; and the harvesting team did not have the ability to mix the entire 2000 lb sack contents uniformly prior to creating 60 lb bucket samples. Therefore, to mitigate the effects of this variability in each 60 lb bucket sample while still meeting the testing timelines, a random sample of buckets received were measured for their fines (cement and sand)-to-aggregates ratio; and then all samples were controlled to that mean ratio with the dry mix weights for both materials controlled to 60 lb. A higher than normal variability in the cement-to-sand ratio then likely still existed. This remaining variability had a moderately negative impact on the predictability of our results in the aluminum sulfate Rapid Set testing (see the *Models for factors prediction, results repeatability* section). However, as will be discussed further, the results and recommendations resulting in each test phase remain conclusive despite this slight degradation in our ability to predict set times and compressive strength gain over time.

2.3 Mixing

The batch sizes in all Rapid Set and Utility Fill testing varied from 3 lb to 60 lb (5 gal. bucket size). Because of the small size of batches in these investigations, materials were able to be suitably mixed with several modifications to ASTM Standard C192 (ASTM International 2007). If chemical admixtures were used, they were dissolved in the mixing water at the desired initial water temperature (in many cases, tap water at 6°C–10°C). The water solution was then brought to the desired testing temperature (from −5°C to 90°C). For each mix, we identified a target w/c and held out a small amount of water to add only as necessary (the amount varied depending on the batch size) to incrementally reach a target slump or workability estimate (5 in. slump for Rapid Set testing; 10 in. slump for Utility Fill as indicated in the objectives section [Section 1.3]).

We used a handheld mixer (a drill with an attachment) and added all dry materials to a large mixing trough. We then added two-thirds of the water solution and all dry materials (Rapid Set or Utility Fill). We mixed the Utility Fill or Rapid Set for 2–3 min and visually inspected it for workability prior to adding additional water solution as necessary. Mixing was continued. Mixing occurred for a total of 3–5 min prior to conducting a slump test (see *Material evaluation tests* section).

2.4 Sample preparation and curing

All materials were staged in cold rooms at the desired ambient and materials' nominal temperature (−15°C, −10°C, −5°C, 0°C, 5°C, 10°C, 20°C) for a minimum of 24 hr prior to testing. We monitored cold rooms for their average daily temperature and recorded detailed data (minute readings) to ensure low instant temperature variability. Immediately after mixing, each Rapid Set or Utility Fill mix was cast into plastic cylindrical molds (size varied depending on batch size: 2-in. diameter × 4-in. height, 3-in. diameter × 6-in. height, 4-in. diameter × 8-in. height), tapped with a mallet to ensure consolidation, not capped (to simulate realistic operational procedures), and stored in the same room at the desired ambient temperature.

2.5 Material evaluation tests

2.5.1 Slump and workability

A combination of slump tests and mixture workability estimates (less precise) were conducted for all mortar and concrete mixes during initial mixing. Slump tests were conducted per ASTM standard C143 (ASTM International 2002). Initial workability was measured for some Rapid Set and Utility Fill mixtures and on a 1–10 scale (1 = unworkable/stiff, 10 = liquid pour). Because of time limitations, we conducted a modification of ASTM D6103-97, "Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)" (ASTM International 1997), to measure the flow consistency of the Utility Fill, using a combination of a slump estimate (10 in. ± 2 in. criterion) and an initial workability estimate. Because concrete mixing is often performed under poorly controlled internal and external factors in this field expedient application, we attempted to produce in the end recipes for the Rapid Set with a reliable 4–7 workability (mildly to extremely workable with no visible component materials segregation) or 4–6-in. slump while adhering to all other performance requirements. Utility Fill recipes were designed for an imprecise slump estimate of 10 in. ± 2 in. and a workability estimate of 10. Water–cement ratios listed in subsequent sections are imprecise estimates as the precise quantities of cement, fine aggregates, and course aggregates (Rapid Set only) are unknown in both pre-mixed materials. Because of time constraints, only the ratio of fines to course aggregates was measured in the samples (omitting the ratio of cement to fine aggregates).

2.5.2 Set time

Measuring set time was a requirement for all samples for both the Utility Fill and Rapid Set materials because we wanted to alter and control the variety of factors, such as the type of cement, w/c, temperature, and the addition of chemical admixtures (Klieger and Lamond 1994), that may influence concrete set times. Testing was conducted in accordance with ASTM C403 (ASTM International 2008b) using a Humboldt Universal Penetrometer (Figure 1). Only minor modifications were made to the standard, such as the test was conducted at different time intervals than recommended so that we could capture the early strength gain information. The test monitored the stiffening of fresh concrete as the hydration process proceeded after the initial contact of water and binder material (Mindess and Young 1981). The designated values of initial and final set were set at 500 and 1000 psi, respectively. Initial set was considered to be the point at which fresh concrete had lost its workability, and final set was when the concrete began to gain significant strength. In this application, the initial set was the primary target of investigation; and any penetration resistance readings beyond 500 psi were used only as an indicator of strength gain during the admixture investigations phase of testing.

Figure 1. Humboldt Universal Penetrometer used for all penetration resistance testing to estimate set times.

2.5.3 Two-hour unconfined compressive strength

Measuring UCS was a requirement for all samples for the Rapid Set because a design strength of 2500 psi UCS was previously determined by the sponsor as the minimum strength necessary for this expedient runway repair application. All UCS testing was conducted in accordance with ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* (ASTM International 2008a), using a 300K lb Riehle compressive strength machine (Figure 2).

Figure 2. A 300K lb Riehle machine (shown above) was used to conduct all unconfined compressive strength testing.

3 Summary of Related Historical Research

3.1 Introduction

Cold weather concreting using admixtures has been of interest since the 1950s with much of the research conducted first by the Russians and followed by the Scandinavian countries in the 1980s. Korhonen (1990) summarizes this earlier research conducted by the Russians and Scandinavians. The research by Korhonen and colleagues in the 1990s and early 2000s forms the basis of cold concreting knowledge in the United States. During this period, Korhonen and others published a dozen reports on behalf of the U.S. Army Corps of Engineers (USACE), ERDC-CRREL (Korhonen 1990, 1999, 2002a, 2002b, 2006; Korhonen and Brook 1996; Korhonen and Orchino 2001; Korhonen and Semen 2005; Korhonen et al. 1997a, 1997b, 1997c, 2004). These reports evaluated different types, combinations, and concentrations of admixtures for cold weather concreting at temperatures from 5°C to −20°C.

Given the current project goals, the relevance of the body of research cited above is somewhat limited to the application of runway repair. For example, the maximum set-time criteria for the CTS Rapid Set Concrete were limited to 45 min and 30 min for the Utility Fill. However, very few of the studies cited above recorded the set time of the concrete. In addition, the minimum compressive strength desired at 2 hr for the CTS Rapid Set Concrete is 2500 psi and 250 psi for the Utility Fill. However, none of the studies cited above determined the compressive strength of the various concrete admixtures at 2 hr. In most instances, the earliest compressive strength measurements were conducted at 7 days and then periodically on 7-day intervals out to 56 days in some instances. Although compressive strength versus time is somewhat linear in the interval of 7 to 56 days, this is not the case over shorter time intervals. Compressive strength versus time over the first 24 hr to several days is expressed as a polynomial or power curve. Thus, the ability to extrapolate from the late-time compressive strengths to predict the compressive strength at the early-time conditions is limited.

3.2 Materials and effects summary

A number of different admixtures can be added to concrete to depress its freezing point; to improve strength, workability or slump, and resistance to freezing; to accelerate the reaction; to reduce the water requirement; or to improve strength. Table 1 lists a number of salt and salt mixtures that lower the freezing point of water and have potential use for cold weather concreting. The admixtures identified with an asterisk following the name are those identified to be in common use although it was acknowledged that the chloride based compounds caused corrosion problems (Korhonen 1990). Korhonen's (1990) compilation of data indicates the highest 28-day compressive strength was observed with the addition of ammonium hydroxide, followed by sodium chloride, then calcium chloride with sodium nitrite. The U.S. Army's patented admixture of sodium nitrate and sodium sulfate at a dosage of 4.5% and 1.5%, respectively, is recommended for cold weather concreting (Korhonen et al. 1997c).

Some of the same materials listed in Table 1 are also used as accelerants to speed up the reaction rate, to accelerate settling, and to increase early strength gain (Table 2). Korhonen et al. (1997c) identified some of the best accelerators, associated freezing point temperature by dosage, and found that higher dosages yielded lower freezing points (Figure 3). Calcium nitrate ($Ca[NO_3]_2$)with a dosage of 8.5% by cement weight yielded a freezing point below −8°C. Admixtures that produced the best strength coupled with rapid setting included sodium nitrate + potassium carbonate, sodium nitrite + sodium sulfate, sodium nitrite + calcium nitrite, and sodium nitrite.

Table 1. Freezing point depressants potentially useful for cold weather concreting.

Types of Admixtures	Compound Name
NH4OH	ammonium hydroxide
CaCl2	calcium chloride*
CaCl2 + NaNO2	calcium chloride + sodium nitrite*
CaCl2 + Ca(NO3)2	calcium chloride + calcium nitrate
Ca(NO3)2	calcium nitrate
Ca(NO3)2 + CO(NH2)2	calcium nitrate + urea*
Ca(NO3)2 + Na2SO4	calcium nitrate + sodium sulfate*
Ca(NO2)2	calcium nitrite
Ca(NO2)2 + CO(NH2)2	calcium nitrite + urea*
Ca(NO2)2 / (NO3)2 + CO(NH2)2	calcium nitrite / nitrate + urea*
[Ca(NO2)2 / (NO3)2 + CaCl2] + CaCl2 + NaNO2	calcium nitrite / nitrate + calcium chloride + sodium nitrite*
Ca(NO2)2 / (NO3)2 +CaCl2 + CO(NH2)	calcium nitrite / nitrate + calcium chloride + urea*
Ca(CH3COO)2	calcium magnesium acetate
Ca(NO3)2 /(H2COH)2	calcium nitrate / ethylene glycol
C2H6O	ethylene alcohol
(H2COH)2	ethylene glycol
LiOH	lithium hydroxide
LiNO3	lithium nitrate
C6H9MnO6 × 2(H20)	manganese acetate
MgCl2	magnesium chloride
Mg(NO3)2	magnesium nitrate
MgSO4	magnesium sulfate
CH4O	methyl alcohol
CH3CO2K	potassium acetate
K2CO3	potassium carbonate*
KCl	potassium chloride
KNO3	potassium nitrate
C2H3NaO2	sodium acetate
NaCl	sodium chloride*
NaCl + CaCl2	sodium chloride + calcium chloride
NaNO3	sodium nitrate
NaNO3 + Na2SO4	sodium nitrate + sodium sulfate
NaNO2	sodium nitrite*
NaNO2 + Na2SO4	sodium nitrite + sodium sulfate*
NaNO2 + Ca(NO3)2 + CaCl2	sodium nitrite + calcium nitrate + calcium chloride*
NH4OH	ammonium hydroxide*
Na2SO4	sodium sulfate
C3H8O	propyl alcohol
C4H6O3	propylene carbonate
C3H8O2	propylene glycol
CH4N2O	urea

*Common admixtures as identified by Korhonen (1990).

Table 2. Accelerators for cold weather concreting.

Types of Admixtures	Compound Name or Vendor
$CaCl_2$	calcium chloride
CaBr	calcium bromide
$Ca(NO_3)_2$	calcium nitrate
$Ca(NO_2)_2$	calcium nitrite
$Ca(C_2H_3O_2)_2$	calcium acetate
$Ca(HCOO)_2$	calcium formate
K_2CO_3	potassium carbonate
DCI	W. R. Grace
Polarset	W. R. Grace
Daraset	W. R. Grace
DP	Master Builders, Inc.*
EY-11	Master Builders, Inc.*
Pozzolith 122-HE	Master Builders, Inc.
Pozzolith NC 534	Master Builders, Inc.
Pozzutec 20	Master Builders, Inc.
Pozzutec 20+	Master Builders, Inc.
Rheocrete CNI	Master Builders, Inc.

* Admixture not commercially available.

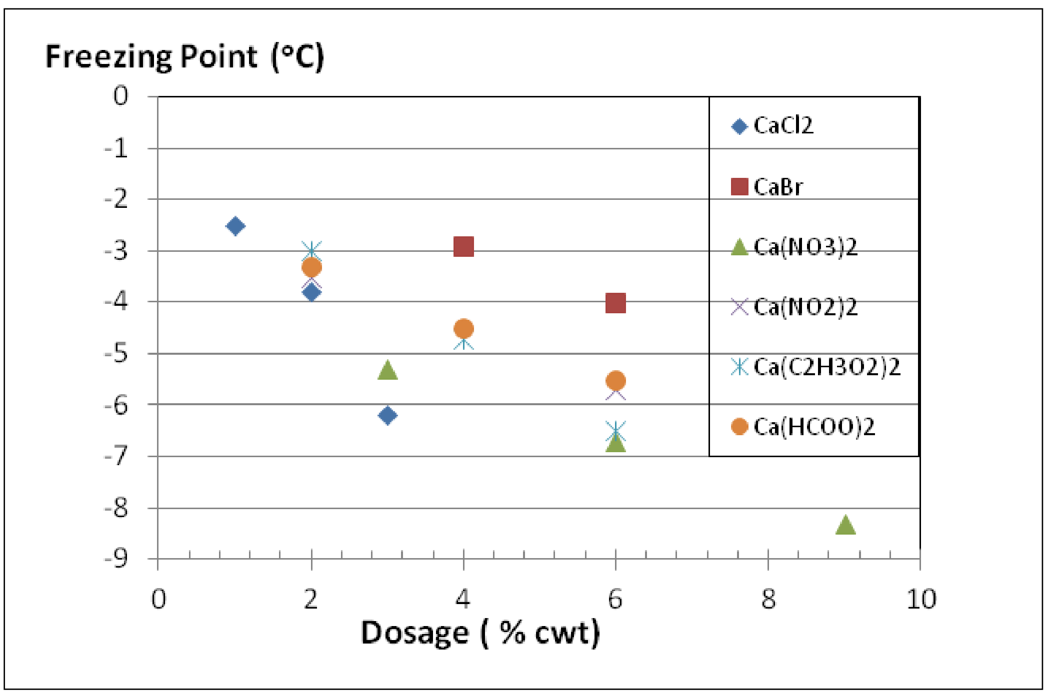


Figure 3. Comparison of freezing point and dosage for various calcium salt admixtures.

A number of the admixtures in Table 2 are proprietary mixtures sold as commercial products, such as the Pozzolith and Pozzutec admixtures. CRREL studied Pozzutec 20 and found that it accelerated the setting of concrete and resulted in a significant strength increase of 20% at 7 and 56 days as compared to regular Portland cement at a temperature of −5°C (Korhonen and Brook 1996). The shortest set time with Pozzutec 20 was slightly less than 3 hr using 90 fl oz/cwt. In contrast, an admixture referred to as EY-11 resulted in poor set times and compressive strengths. Further development by Korhonen et al. (1997a) resulted in EY-11 and another admixture referred to as DP yielding acceptable set times (although not specified) and comprehensive strengths (greater than 6000 psi 6 months later) based on a field study conducted at −5°C. A study of Daraset and Polarset admixture accelerators found that Daraset yielded unacceptable strengths whereas Polarset performed well down to 5°C (Korhonen et al. 1997b).

In addition to depressing the freezing point or accelerating the set time for concrete in cold temperatures, some of the salts listed in Table 1 also improve the strength of concrete under cold conditions (Table 3). Korhonen (1990) showed that the admixtures containing calcium improved the 7-day compressive relative to a 28-day control sample by up to 124% at 20°C. However, the strength improvements declined with decreasing temperature and by −5°C were quite modest (e.g., 3% to 68% improvement). Calcium chloride and calcium nitrate were the best strength enhancers.

Table 3. Strength enhancers for cold weather concreting.

Types of Admixtures	Compound Name or Vendor
$Ca(C_2H_3O_2)_2$	calcium acetate
$CaBr_2$	calcium bromide
$CaCl_2$	calcium chloride
$Ca(HCOO)_2$	calcium formate
$Ca(CH_3COO)_2$	calcium magnesium acetate
$Ca(NO_3)_2$	calcium nitrate
$Ca_3(PO_4)_2$	calcium phosphate
CH_3CO_2K	potassium acetate
Na_2SO_4	sodium sulfate
$Na_2SO_4 + NaNO_3$	sodium sulfate + sodium nitrate

Plasticizers or super plasticizers are also added to the various cold weather concrete admixtures to improve workability or slump, to reduce the water requirement, or to improve strength (Table 4).

Table 4. Plasticizers or super plasticizers for cold weather concreting.

Plasticizers	
Types of Admixtures	**Compound Name or Vendor**
lignosulphonic acids and salts	Various
hydroxylated carboxylic acids and salts	Various
Polyheed 997	Master Builders, Inc.
Pozzolith 322-N	Master Builders, Inc.
Super Plasticizers	
sulphonated melamine formaldehyde	Various
sulphonated naphthalene formaldehyde	Various
modified lignosulphonates	Various
polycarboxylate materials	Various

In addition, air entrainers are often added to cold weather concrete admixture to improve workability or slump and resistance to freezing (Table 5). Upon thawing, these admixtures can lose up to 5% strength.

Table 5. Air entrainers for cold weather concreting.

Types of Admixtures	Compound Name or Vendor
salts of wood resins	Various
animal fats or oils	Various
vegetable fats or oils	Various
sulphonated hydrocarbons	Various
Daravair	W. R. Grace
Daravair 1000	W. R. Grace
Darex II AEA	W. R. Grace
MB AE 90	Master Builders, Inc.
MB-VR Standard	Master Builders, Inc.
Micro-Air	Master Builders, Inc.

In some cold weather concreting situations, water reducers are needed or retarders are needed if the concrete sets too quickly at the working temperature. Table 6 is list of water reducers or water reducers and retarders.

Table 6. Water reducers and retarders for cold weather concreting.

Types of Admixtures	Compound Name or Vendor
Water Reducers	
WRDA 19	W. R. Grace
WRDA 82	W. R. Grace
WRDA w/ Hycol	W. R. Grace
Daracem 19	W. R. Grace
Daracem 55	W. R. Grace
Daracem 65	W. R. Grace
Mira 70	W. R. Grace
Polyheed 997	Master Builders, Inc.
Pozzolith 122-N	Master Builders, Inc.
Pozzolith 322-N	Master Builders, Inc.
Rheobuild 1000	Master Builders, Inc.
Rheobuild 3000 FC	Master Builders, Inc.
Glenium 3000 NS	Master Builders, Inc.
High Range Water Reducers	
Daracem 19	W. R. Grace
Daracem 100	W. R. Grace
Mira 70	W. R. Grace
Adva Flow	W. R. Grace
Adva 100	W. R. Grace
Polyheed 997	Master Builders, Inc.
Rheobuild 1000	Master Builders, Inc.
Rheobuild 3000FC	Master Builders, Inc.
Glenium 3000 NS	Master Builders, Inc.
Water Reducers and Accelerators	
Daraccel	W. R. Grace
Pozzolith 122-HE	Master Builders, Inc.
Pozzutec 20	Master Builders, Inc.
Pozzutec 20+	Master Builders, Inc.
Water Reducers and Retarders	
Daratrad 17	W. R. Grace
Recover	W. R. Grace
Delvo Stabilizer	Master Builders, Inc.
Pozzolith 100-XR	Master Builders, Inc.
High Range Water Reducers and Retarders	
Daracem 100	W. R. Grace

In other situations, only a retarder is needed for cold weather concreting. Table 7 provides a list of retarders.

Table 7. Retarders for cold weather concreting.

Retarders	
hydroxylated carboxylic acids	Various
lignins	Various
sugar	Various
phosphates	Various
Daratard 17	W. R. Grace
Delvo Stabilizer	Master Builders, Inc.
Pozzolith 100-XR	Master Builders, Inc.

Korhonen and Orchino (2001) found that a combination of calcium chloride with an accelerant, water reducer and accelerant, and high-water reducer were the best combination for lowering the freezing point and for rapid concrete set, workability, and strength although this report did not specifically identify the admixtures or dosages desirable to mix with concrete. Similarly, Korhonen (2002a) found that a combination of admixtures worked well and met his criteria for cold weather concreting at temperatures below 5°C, but he did not identify the specific admixtures and dosages. Korhonen (2002b) found that concrete admixtures worked best if the mixing water contained more than 3% solutes, and he suggested that some Russian studies indicated dosages as high as 20% worked well. Studies indicated that in the field, off-the-shelf admixtures could be readily mixed with cold water using standard equipment and could yield acceptable concrete at temperatures between 0°C and −5°C (Korhonen 2006).

Based upon the previous findings, most recent studies on cold weather concrete systems have focused on using a combination of several commercially available chemical admixtures. These mixtures have been found to depress the freezing point of the concrete mix water, to protect the fresh concrete at subfreezing temperature (as low as −5°C), and to promote early strength gain without requiring temporary shelters and external heating (Barna et al. 2010b).

Barna et al. (2010a) tested five different combinations (i.e., 5 mixes) of admixture ingredients in a full-scale, winter field trial at Fort Wainwright, AK. The admixtures included Glenium 3000NS, Pozzutec 20+, Rheocrete

CNI, and Rheomac VMA. Only three admixture ingredients were combined for any one mix. They found that all five mixes reached the required 4000 psi compressive strength within 5 days of curing and that all but one of the mixtures (the only mix containing the Rheomac VMA) had continued to gain strength (to about 7000 psi) when tested on day 28. Freezing point measurements revealed that mix 1 had a substantially lower freezing point (25.4°F) than the other four mixes (which ranged from 30.5°F to 29.2°F). This is not surprising given that this mix had a substantially higher percent of total solids than the other four mixes. For mixes 1, 2, 3, and 4, Figure 4 shows the linear relationship between the chemical admixtures in the mix water (percent solids) and the resulting initial freezing point (as initially described by Korhonen et al. [2004]). Mix 1 contained 8 fl oz/cwt Glenium 3000NS, 68.0 fl oz/cwt Pozzutec 20+, and 4 g/yd of Rheocrete CNI. However, the researchers did not follow the gain in strength of these materials within the first few hours. (Rheomac VMA is an admixture that had not previously been used in cold-weather concrete systems. It is a corrosion inhibitor that also enhances concrete viscosity and provides stability against segregation.)

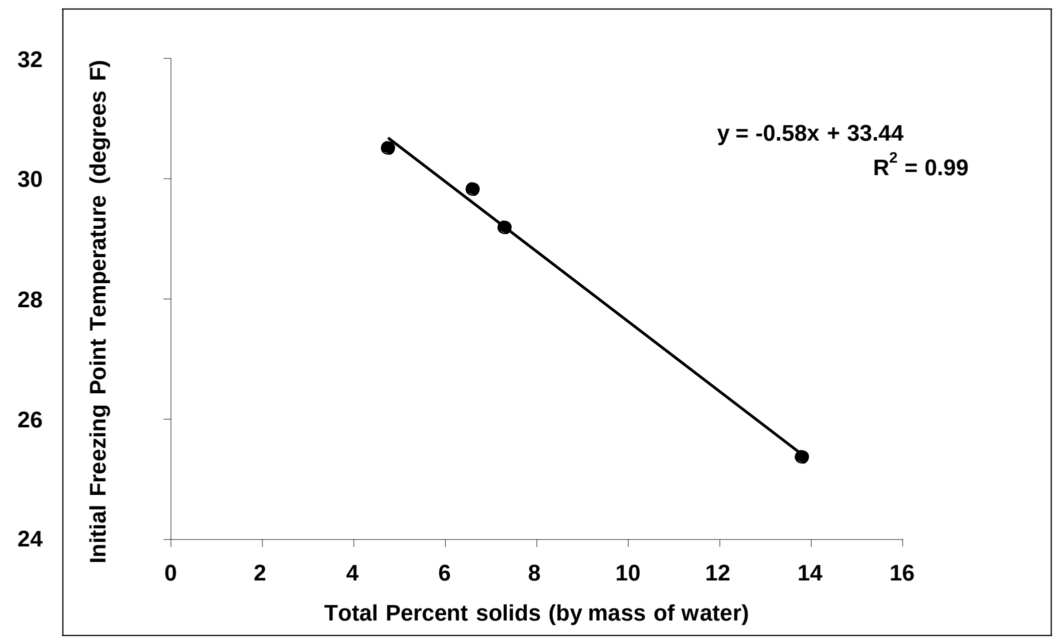


Figure 4. The relationship between freezing point depression and the total percent solids in the mix water.

Cortez et al. (2010) conducted laboratory tests on a combination of Rheocrete CNI and Pozzutec 20+ admixtures for use as cold roller-compacted concrete (cold-RCC). They tested a series of seven combinations of these admixtures. Each combination was an improvement on the previous formulation. They cured samples at room temperature (22.8°C) and in the cold (at O°C and −5°C). The final formulation was tested in a full-scale field demonstration conducted at Fort Drum, NY, where the ambient air temperature was −0.6°C. In the field study, compressive strengths were measured after 1, 3, 7, and 28 days. The final formulation contained 658 lb/yd^3 cement, 2225 lb/yd^3 coarse aggregate, 1094 lb/yd^3 fine aggregate, 249.6 lb/yd^3 added water, 50 lb/yd^3 Rheocrete (with 16.25% solids), and 34.72 lb/yd^3 Pozzutec (with 13.89% solids); and the final calculated moisture content for this formulation was 6.23%. In the field, a second formulation was also tested that contained slightly more added water and had a calculated moisture content of 7.03%.

After 1 day, the lower-moisture mix cured at 22.8°C yielded a compressive strength of 4000 psi. After 3 days, the mix cured at O°C yielded a similar compressive strength; and the mix cured at −5°C yielded a similar compressive strength after 28 days.

Barna et al. (2010b) have also conducted both laboratory and field evaluations of rapid setting cementitious materials for large crater repair. Test materials included Rapid Set DOT Cement, Cera-Tech Pavemend EX-H, Degussa ThoRoc Repair Mortar, Ultimax Concrete, and Ultimax Aquacrete. Although they measured compressive strengths after 2 hr, none of the tests were conducted in the cold.

In laboratory tests conducted by Barna et al. (2010a) at room temperature, only the Rapid Set DOT Cement met the requirements of greater than or equal to 3000 psi at 2 hr and greater than or equal to 5000 psi at 1 and 28 days. The initial set time was 60 min, the final set time was 80 min, and the slump was measured to be 4 in. (water temperature was 22°C). However, the performance of the ThoRoc Repair Mortar 10-61 was also relatively good with a compressive strength greater than 3000 psi after 4 hr and nearly 5000 psi at 1 and 28 days. The laboratory tests conducted at 32°C clearly showed reduced compressive strengths for all the materials tested with increased initial and final set times. Barna et al. (2010a) concluded that this illustrated the need to test materials under the anticipated temperature conditions.

For the field tests, Barna et al. (2010b) repaired large craters that they then subjected to trafficking with a load cart (after 4 hr) equipped with an F-15E tire. The air temperatures were 32–36°C for this test. Two materials performed best: the Rapid Set DOT Cement and the ThoRoc 10-61 Rapid Repair Mortar. Both sustained over 5000 passes of the F-15 load cart with only low severity cracking. Barna et al. (2010b) also noted that although Pavemend EX-H (a material developed for hot weather) did not perform well in the laboratory tests, it performed well in the field test.

4 Utility Fill and Rapid Set Concrete Materials Analyses

4.1 Introduction

The primary focus of the materials analyses phase was to identify various compounds of the two concrete mixtures, Utility Fill and Rapid Set, before and after hydration and setting. This information would provide their chemical composition, mineralogy and hydraulic reactivity, and the chemical changes that contribute to the physical and mechanical properties of the concrete. These analyses may also isolate the effect of admixtures. The information will also provide insight to improve the unconfined compressive strength and the setting kinetics through modifications to the composition of the two concrete mixtures. The analyses conducted are primarily divided into three categories: physical properties, chemical properties, and thermal properties. Morphological observations were conducted using scanning electron microscopy (SEM) and chemical composition and mineralogy—using wavelength-dispersive X-ray fluorescence spectroscopy, X-ray diffraction, and Blaine fineness (i.e., surface area). To characterize changes in the resulting microstructure, SEM was conducted on hydrated samples and, in some cases, an accelerating admixture. Chemical analysis included Fourier Transform Infrared (FTIR) spectroscopy, which basically provides various chemical functional groups. We evaluated thermal analysis and early-age hydraulic reactivity by using in-situ isothermal calorimetry techniques to monitor in real time setting and the heat flow associated with cementation reactions.

4.2 Materials

As described in previous sections, the two materials of interest for this study were Utility Fill and Rapid Set. CRREL sent to CERL and GSL samples of Utility Fill and Rapid Set concrete before and after hydration. Some samples were hydrated on-site at CERL and GSL. Since the primary interest in these materials was how the early-age properties can be improved, many of the characterization efforts focused on the cementing phase of each material (only about 7% and 35% by mass in Utility Fill and Rapid Set, respectively). To isolate the cement fraction of each material, the lab passed the as-received material through a #325 (44 µm) sieve to remove the aggregate. X-ray diffraction measurements, described in a subsequent section, verified the success of this method.

4.3 Methods

The following sections provide a brief description of the instruments and the approaches to characterization of the materials.

4.3.1 Morphology, chemistry, and mineralogy

4.3.1.1 Scanning electron microscopy

Using SEM, we characterized the microstructure present in Utility Fill and Rapid Set cements with water and accelerator solutions. The samples measured included Utility Fill with water (H_2O), Rapid Set with water, Rapid Set with a 15% calcium chloride ($CaCl_2$) solution, and Rapid Set with a 10% aluminum sulfate hydrate solution. All samples had a w/c of 0.6. Samples were imaged after at least 3 days of hydration. Specimens for SEM imaging were freshly fractured and affixed to SEM stubs with the exposed fracture surface facing up for imaging. We imaged the specimens by using an FEI Nova NanoSEM 630 variable pressure field emission SEM. Using a backscattered electron detector to reveal changes in microstructure and the distribution of phases according to their respective densities, we performed imaging at an accelerating voltage of 5 to 15 kV and used low-vacuum environmental mode (pressure of 0.1–1.0 mb) to minimize charging and dehydration of the samples.

4.3.1.2 Wavelength-dispersive X-ray fluorescence spectroscopy

Using X-ray fluorescence spectroscopy (XRF), we determined the measurements of the chemical composition of the cement fraction isolated from the Utility Fill and Rapid Set materials. All analyses used a Panalytical Axios Cement XRF spectrometer. Internal calibrations for all relevant elements present in cement-based materials were used to quantify the chemical composition. Using a Claisse fluxy with a lithium borate fluxing medium, we prepared samples as fused disks. Additionally, we prepared a full oxide analysis of relevant elements detected for each cement, normalizing the full composition by an external loss-on-ignition (LOI) experiment.

4.3.1.3 X-ray diffraction

X-ray diffraction (XRD) determined the measurements of the mineralogy of the cement fraction extracted from the Utility Fill and Rapid Set materials. Using a Panalytical X’Pert Pro materials research diffractometer equipped with a Co-Kα X-ray source operated at 45 kV and 40 mA, the team obtained diffraction patterns to be used for quantitative phase identification. Random powder-pack samples were prepared from the cement that had already passed a #325 sieve. Diffraction patterns were obtained over a period of 2 hr from 2° to 70° 2θ with a step size of 0.02° 2θ. MDI Jade 2010 software with access to the powder diffraction file database performed the phase identification.

4.3.1.4 Blaine fineness/reactive surface area

Using the Blaine fineness technique according to C204-11, “Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus” (ASTM International 2011) we determined the measurements of the reactive surface area (i.e., the surface area available for hydraulic reactions to initiate) of the cement fraction extracted from the Utility Fill and Rapid Set materials.

4.3.2 Chemical interactions

The predominant chemical functional groups present in the two cement mixtures were obtained using FTIR spectroscopy. The chemical composition and mineralogical information was also obtained using XRF and XRD as described above.

Samples of the concrete were ground to a fine powder before analyses. We used a JASCO instruments (JASCO Analytical Instruments, Easton, MD) model FT/IR-4100 Spectrometer to obtain the spectra within the range of 500–4000 cm^{-1} with a resolution of 4 cm^{-1}, and we obtained spectra of concrete mixtures before and after hydration for comparison and to isolate chemical changes after hydration.

4.3.3 Thermal properties

4.3.3.1 Isothermal calorimetry

Using isothermal calorimetry, we investigated measurements of the early-age heat flow associated with hydraulic reactions. The samples measured included Utility Fill with water, Rapid Set with water, Rapid Set with a 15% calcium chloride solution, and Rapid Set with a 10% aluminum sulfate hydrate solution. We took all measurements with a TA Instrument TAM Air isothermal calorimeter operated at 23°C. To capture the initial wetting of the cement and early-age reactions, an in situ mixing ampoule was used rather than mixing externally to the calorimeter and inserting which would not capture any early-age phenomena. We prepared the appropriate masses of solution and cement and inserted them into the in situ mixing ampoule, which was then inserted into the calorimeter. Following ampoule insertion, we allowed the system to stabilize for at least 1 hr. Once stabilized, we inserted the solution into the ampoule and mixed it with the cement. Samples were prepared with a w/c of 0.6 to ensure full wetting of the cement. All tests were carried out to an age of 6 hr. We collected early-age heat flow curves and calculated integrated heats of hydration.

4.3.3.2 Thermogravimetry analysis

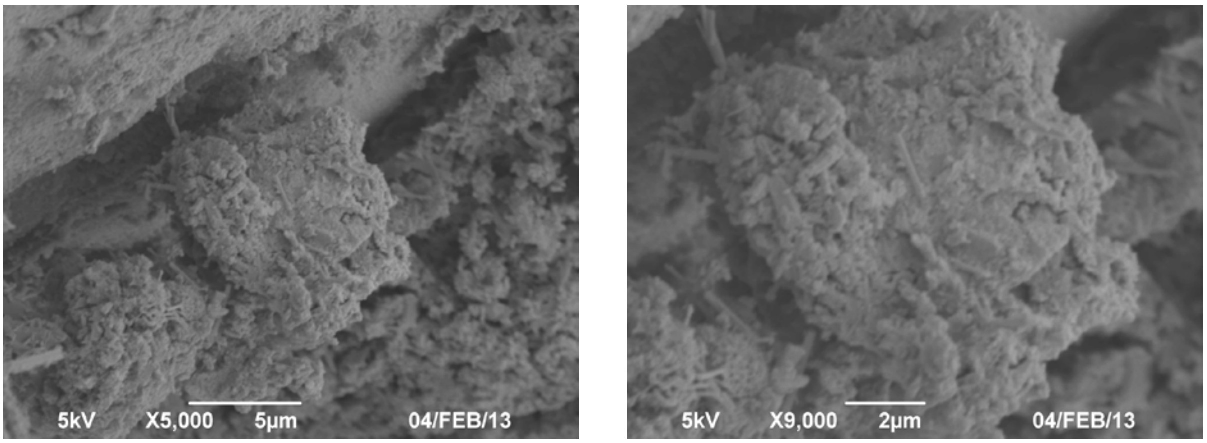
We used a Shimadzu Model TGA 50 (Shimadzu Corporation, Kyoto, Japan) to obtain thermograms of Rapid Set and Utility Fill samples (hydrated and non-hydrated). Weight loss profiles were taken from room temperature to 1000°C in a nitrogen atmosphere with a heating rate of 10°C/min and with a resolution of 0.001 mg. These thermograms could provide a thermal fingerprint of the materials. Based on the weight loss during a specific temperature range, one can identify the amount of hydration and other chemical changes. Samples with admixtures were not tested during the preliminary study.

4.4 Results and discussion

4.4.1 Morphology, chemistry, and mineralogy

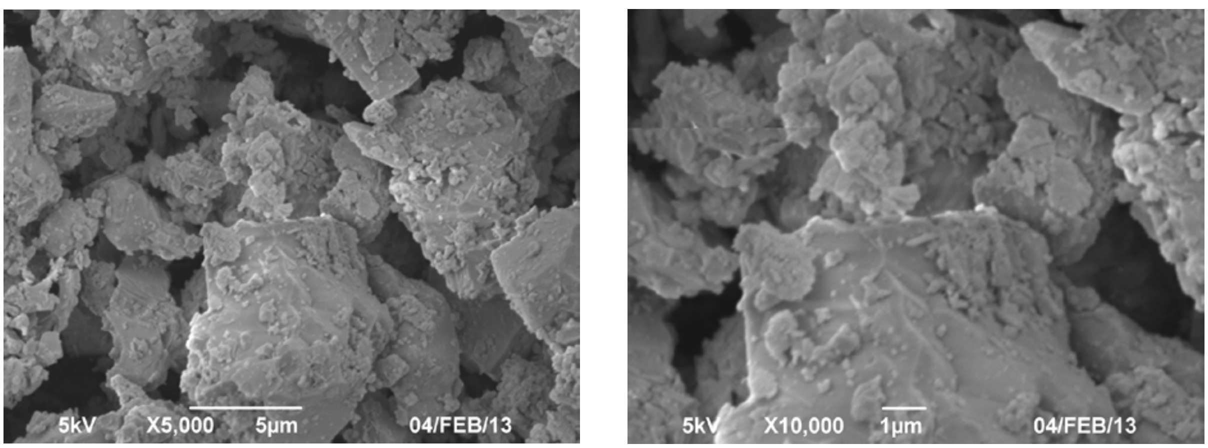
4.4.1.1 Gross morphology and microstructural characterization

CERL collected at their facilities the gross morphology of samples of Utility Fill and Rapid Set (Figures 5 and 6). They crushed samples into granules both before and after hydration, and the granules then were gold sputtered. The scanning electron micrographs were obtained using a Scanning Electron Microscope model JSM-6390 from JEOL USA, Inc. (Peabody, MA). GSL provided SEMs showing more detailed microstructures of the samples (Figures 9–12).



(a) 5K× magnification (b) 9K× magnification

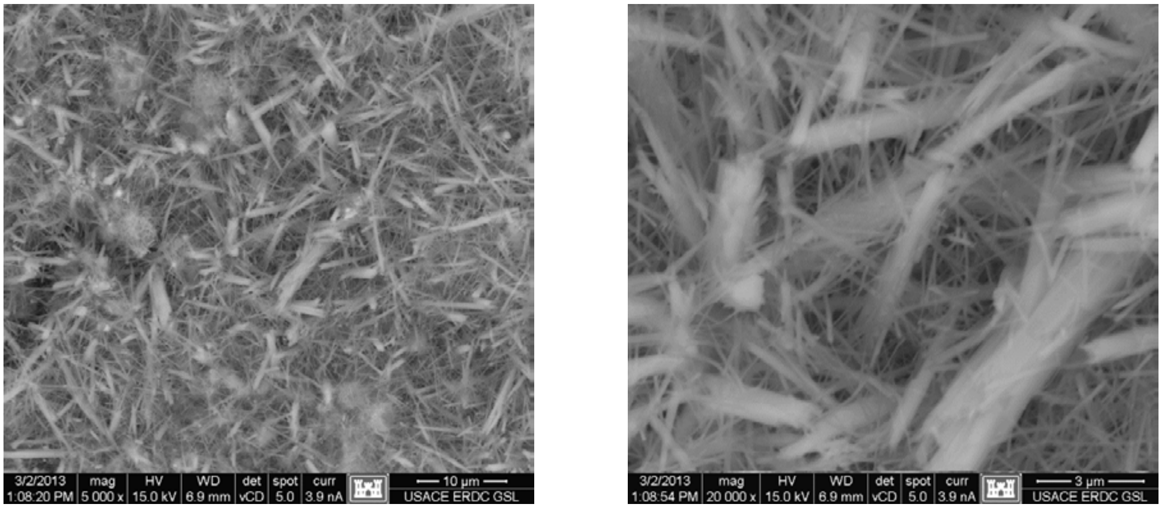
Figure 5. SEMs of Utility Fill before hydration.



(a) 5K× magnification (b) 10K× magnification

Figure 6. SEMs of Rapid Set Concrete Mix before hydration.

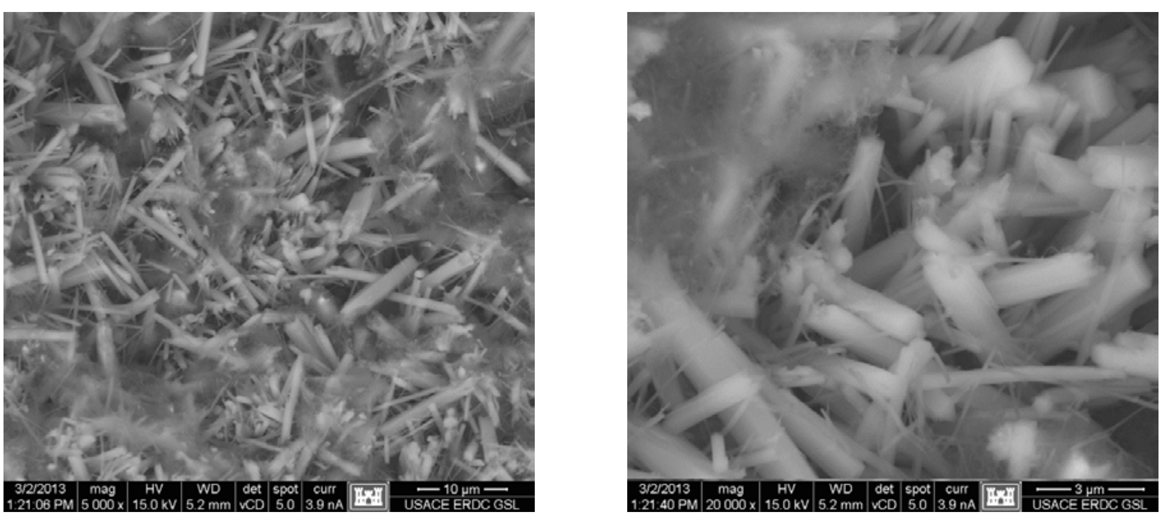
SEM imaging of the fracture surfaces investigated the microstructure of samples prepared by reacting the cementitious material from Rapid Set and Utility Fill materials with various solutions. Figure 7 shows the typical microstructure observed in the Rapid Set material when reacted with water. The microstructure is dominated by acicular ettringite (a calcium aluminosulfate hydrate) and some large calcium sulfate ($CaSO_4$) precipitates and is consistent with the microstructure typically observed at early ages with CSA cements.



(a) 5K× SEM micrograph (b) 20K× SEM micrograph

Figure 7. Low and high magnification images of the microstructure present in Rapid Set with water.

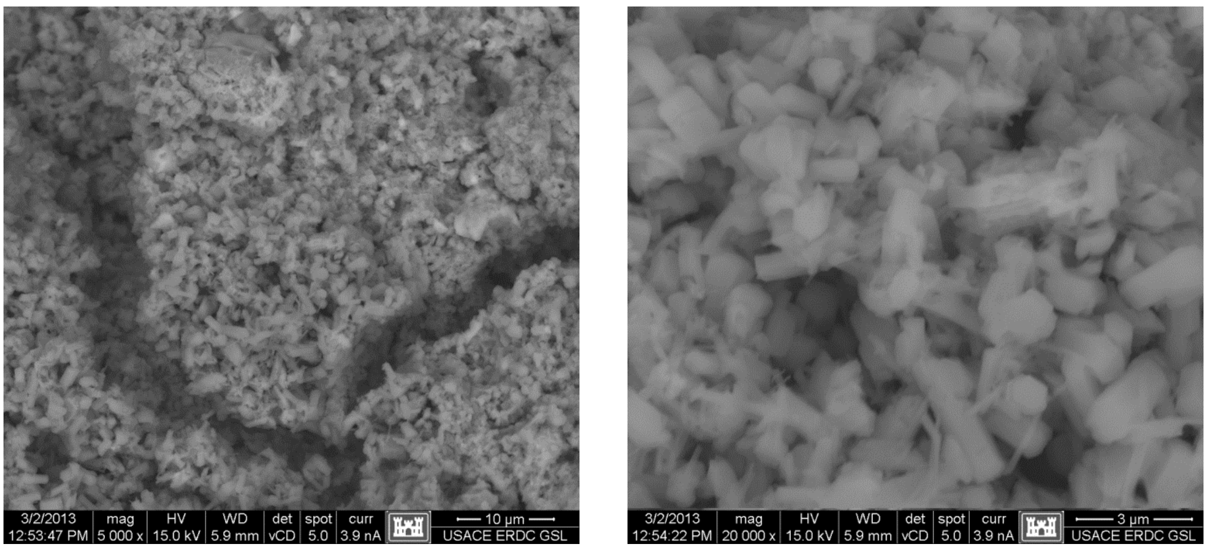
Figure 8 shows the microstructure present when Rapid Set material was reacted with water including an aluminum sulfate accelerating admixture. Acicular ettringite needles, similar to when water was used alone, were present along with gel-like material that bound the ettringite needles together. Overall, the microstructure was more dense and likely stronger and less permeable than when aluminum sulfate was not present.



(a) 5K× SEM micrograph (b) 20K× SEM micrograph

Figure 8. Low and high magnification images of the microstructure present in Rapid Set with aluminum sulfate.

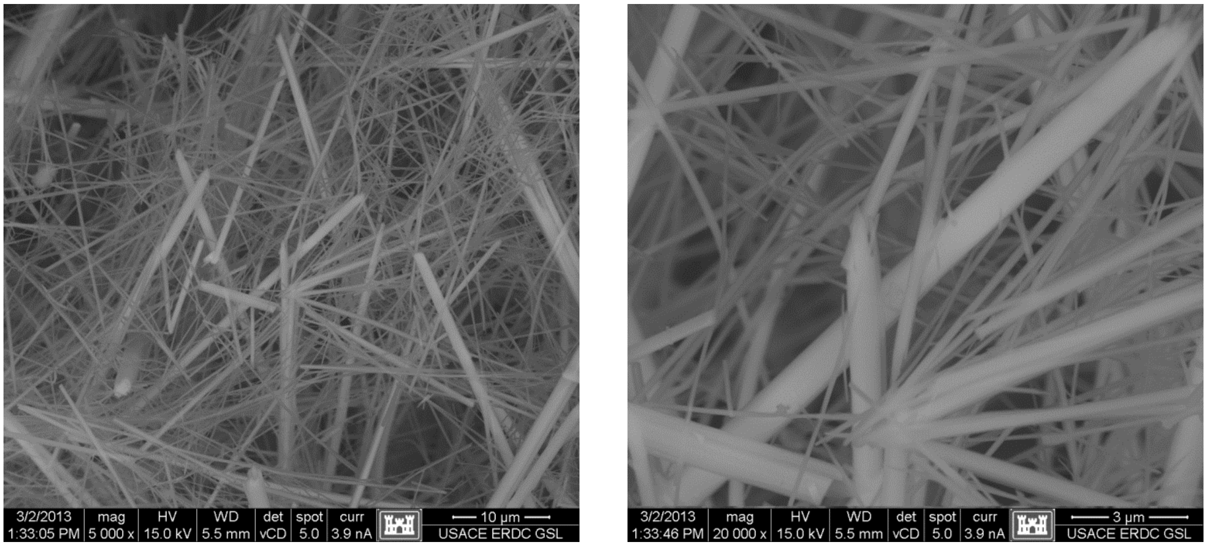
When calcium chloride was used as the accelerating admixture along with Rapid Set material, we observed a significant change in the microstructure (Figure 9). Ettringite needles, which are typically present in the microstructure of CSA-based cementitious composites, were not present. Rather, short, weakly bonded crystals that were likely a mixture of Friedel's salt (a calcium aluminum chlorohydrate) and calcium sulfate phases were present. The presence of these phases is evidence of reduced early-age strength and set times.



(a) 5K× SEM micrograph (b) 20K× SEM micrograph

Figure 9. Low and high magnification images of the microstructure present in Rapid Set with calcium chloride.

Figure 10 provides images of the typical microstructure observed in hydrated Utility Fill samples. Ettringite needles completely dominated the microstructure, which is consistent with a material that is largely composed of CSA cement, and corroborates the reduced calcium oxide (CaO) and silicon dioxide (SiO_2) content measured in the Utility Fill cementitious fraction by XRF.



(a) 5K× SEM micrograph (b) 20K× SEM micrograph

Figure 10. Low and high magnification images of the microstructure present in Utility Fill with water.

4.4.1.2 Mineralogy and chemical analysis

Table 8 provides the results from XRF chemical analyses of the cement fraction of Rapid Set and Utility Fill materials. The high sulfur trioxide (SO_3) and aluminum oxide (Al_2O_3) compositions present in both materials along with the relatively low calcium oxide content (typically about 60% in Portland cements) are indicative of an alternative cement chemistry likely associated with a CSA cement. As a result, traditional Bogue equations for calculating the proportion of phases in a traditional Portland cement (C_3S, C_2S, C_3A, and C_4AF*) are not applicable; and quantitative XRD should be used. The high LOI values measured (ASTM C150 limits LOI to 3.0% [ASTM International 2012]) are likely associated with organic impurities present in the aggregates of the Rapid Set and Utility Fill materials that passed through the #325 sieve and were additive with the LOI of the cementitious phase itself.

Figures 11 and 12 provide results from XRD analyses, including qualitative phase identification and quantitative analysis results obtained from whole pattern fitting, for the cementing phase of Utility Fill and Rapid Set cements, respectively. In both cases, phases observed in only CSA cements

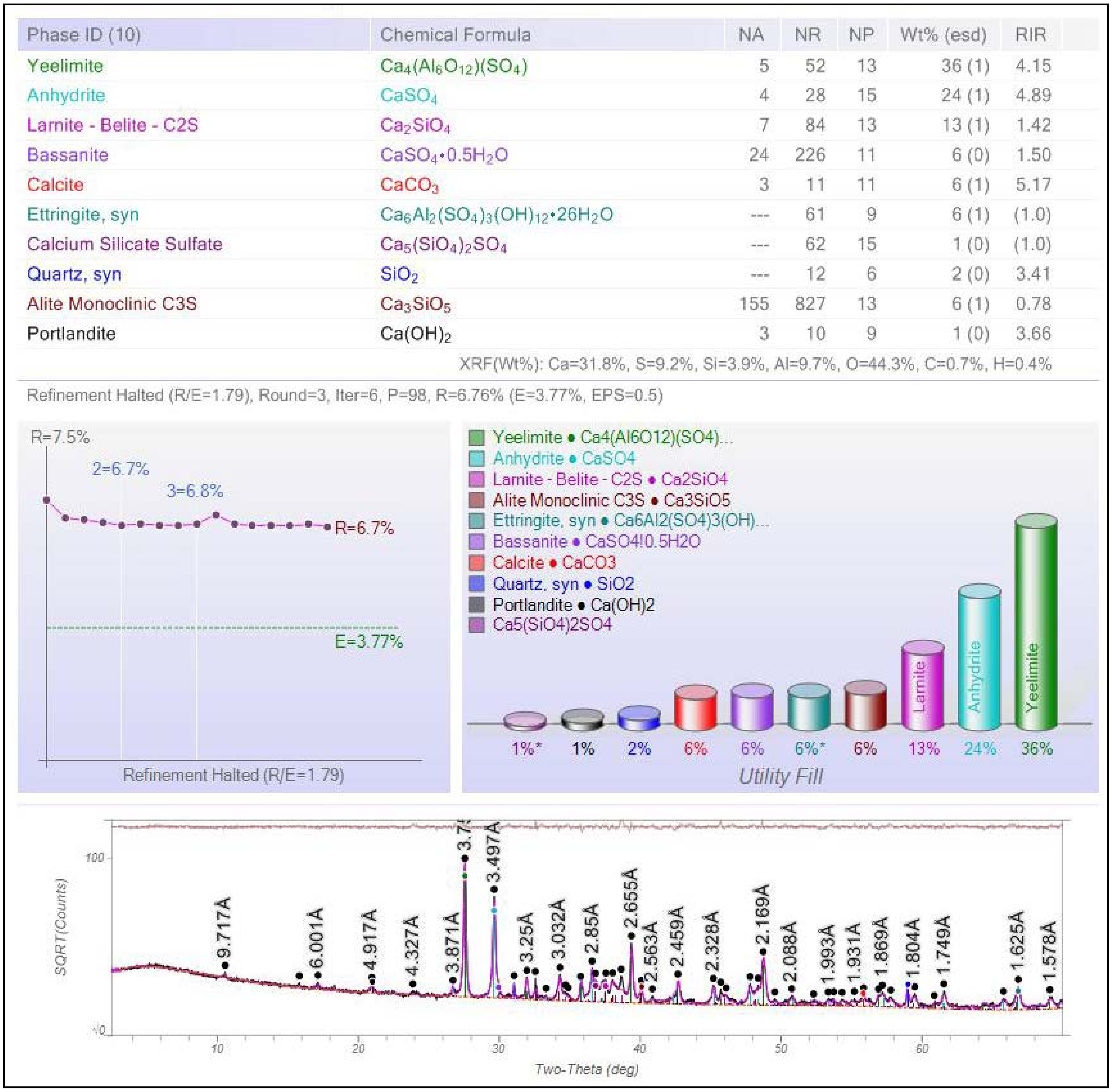
* Cement chemist notation for tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium alumino ferrite.

were present, including Yeelimite, Belite, Bassanite, and Anhydrite. Only trace amounts of quartz were observed, confirming the effectiveness of the sieving procedure in removing the siliceous aggregates and in isolating the cementitious fraction of each material. Trace peaks for various hydration products, including ettringite and portlandite, were observed in the Utility Fill material, indicating minor hydration likely associated with exposure to ambient relative humidity. In the Rapid Set material, an increased amount of Larnite (C_2S) was observed, which corroborates the increased calcium oxide and silicon dioxide contents measured by XRF.

Table 8. XRF oxide analysis results for the cement fraction of Utility Fill and Rapid Set.

Sample ID	Utility Fill (cement fraction) Wt. %	Rapid Set (cement fraction) Wt. %
SiO_2	13.13	14.45
Al_2O_3	19.87	15.34
Fe_2O_3	2.16	1.03
CaO	38.46	47.63
MgO	0.81	1.39
SO_3	17.50	14.61
K_2O	0.50	0.62
Na_2O	0.17	0.26
P_2O_5	0.11	0.08
TiO_2	0.86	0.64
Mn_2O_3	0.05	0.02
SrO	0.08	0.16
ZnO	0.004	0.018
LOI	6.30	3.76
Total	**100.00**	**100.00**

Results of chemical and mineralogical analyses confirmed the present of CSA cement in both Rapid Set and Utility Fill materials. The presence of CSA is an important consideration when selecting accelerating admixtures for cold weather applications as many accelerators typically used for Portland cements (e.g., Type, I, I/II, and III) will not have the same effect when CSA cementing chemistries are present.

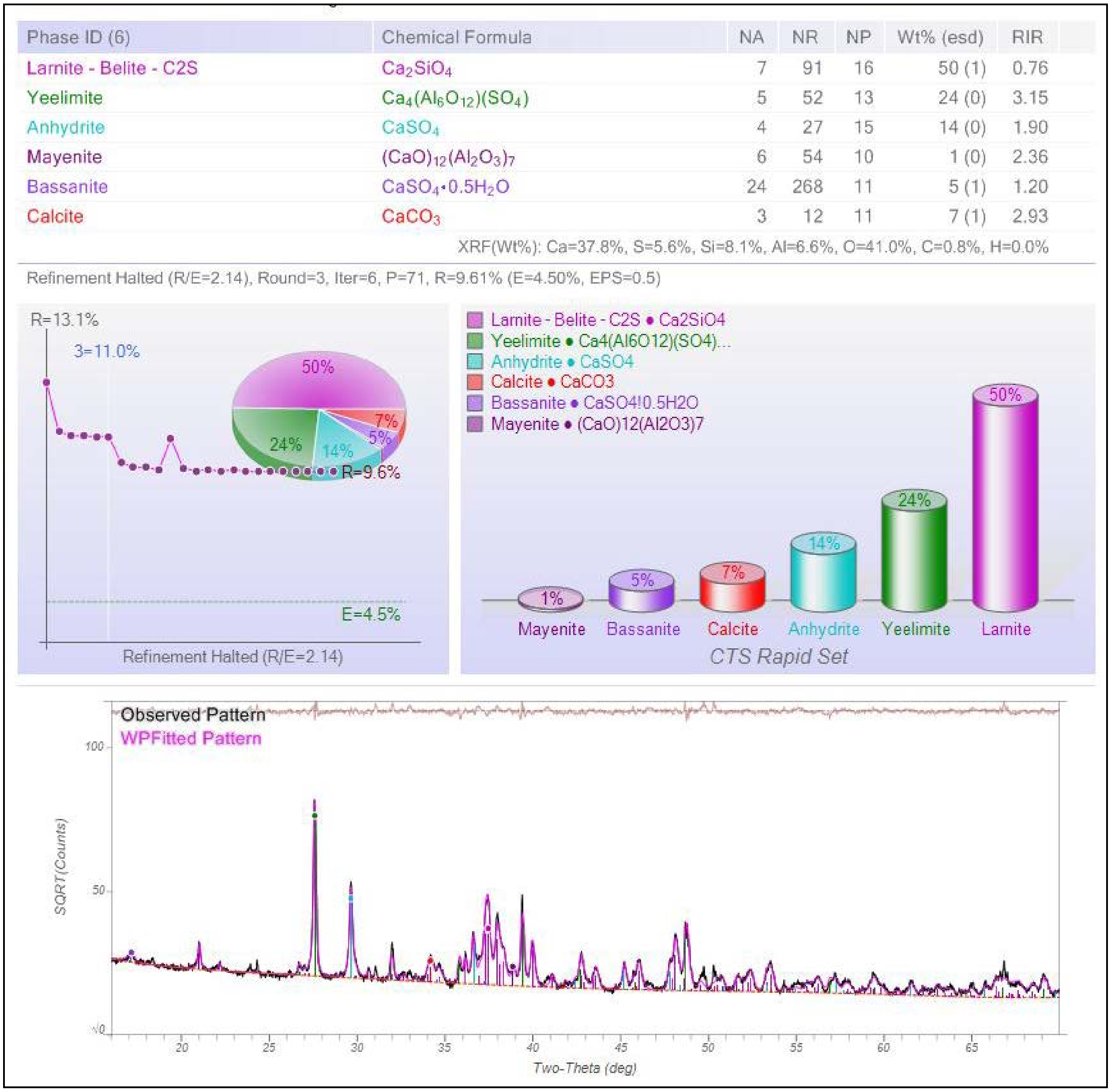


Phase ID (10)	Chemical Formula	NA	NR	NP	Wt% (esd)	RIR
Yeelimite	$Ca_4(Al_6O_{12})(SO_4)$	5	52	13	36 (1)	4.15
Anhydrite	$CaSO_4$	4	28	15	24 (1)	4.89
Larnite - Belite - C2S	Ca_2SiO_4	7	84	13	13 (1)	1.42
Bassanite	$CaSO_4 \cdot 0.5H_2O$	24	226	11	6 (0)	1.50
Calcite	$CaCO_3$	3	11	11	6 (1)	5.17
Ettringite, syn	$Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$	---	61	9	6 (1)	(1.0)
Calcium Silicate Sulfate	$Ca_5(SiO_4)_2SO_4$	---	62	15	1 (0)	(1.0)
Quartz, syn	SiO_2	---	12	6	2 (0)	3.41
Alite Monoclinic C3S	Ca_3SiO_5	155	827	13	6 (1)	0.78
Portlandite	$Ca(OH)_2$	3	10	9	1 (0)	3.66

XRF(Wt%): Ca=31.8%, S=9.2%, Si=3.9%, Al=9.7%, O=44.3%, C=0.7%, H=0.4%

Refinement Halted (R/E=1.79), Round=3, Iter=6, P=98, R=6.76% (E=3.77%, EPS=0.5)

Figure 11. XRD pattern and quantitative analysis results of the cement fraction from Utility Fill.



Phase ID (6)	Chemical Formula	NA	NR	NP	Wt% (esd)	RIR
Larnite - Belite - C2S	Ca_2SiO_4	7	91	16	50 (1)	0.76
Yeelimite	$Ca_4(Al_6O_{12})(SO_4)$	5	52	13	24 (0)	3.15
Anhydrite	$CaSO_4$	4	27	15	14 (0)	1.90
Mayenite	$(CaO)_{12}(Al_2O_3)_7$	6	54	10	1 (0)	2.36
Bassanite	$CaSO_4 \cdot 0.5H_2O$	24	268	11	5 (1)	1.20
Calcite	$CaCO_3$	3	12	11	7 (1)	2.93

Figure 12. XRD pattern and quantitative analysis results of the cement fraction from Rapid Set.

4.4.1.3 Reactive surface area

We made measurements of Blaine fineness to estimate the reactive surface area available in the cementitious fraction of Utility Fill and Rapid Set materials. Blaine fineness values of 582 m^2/kg and 448 m^2/kg were measured for Utility Fill and Rapid Set materials, respectively. These fineness values are similar to what are typically obtained for Type III Portland cements;

and as a result, one can assume the ground cement particles are of a similar size of 1 to about 15 µm.

4.4.2 Chemical interactions

The XRF and XRD analyses of the cement mixtures show the various mineralogical components and chemical compositions present. IR spectroscopy can aid in further studying specific compounds and their chemical changes during hydration. A focused examination as a function of hydration rates and time and in the presence of admixtures would help to draw conclusions and to design an ideal concrete mixture. This report discusses only a preliminary IR observation of the Rapid Set and Utility Fill to identify the differences in the two cement mixes. As stated in the above section, based on XRF, the Rapid Set has higher calcium oxide and silicon dioxide while the Utility Fill has slightly higher amounts of aluminum oxide, iron oxide (Fe_2O_3), and sulfur trioxide. It is difficult to conclude that these mineral component differences are major contributing factors for the improved early high unconfined compressive strength development in Rapid Set. Rapid Set with aluminum sulfate helped with early strength development. It would be interesting to study chemical changes that take place in these concrete mixtures.

We examined the infrared (IR) spectra, in particular the hydroxyl, silicate and aluminates, and metal oxide compounds. The hydroxyl radicals observed using IR can be from the water molecules that are just surface adsorbed, structurally bound as OH (hydroxide), or from crystal hydrates. However, these can be isolated based on the frequencies they impart to the spectrum. The peaks in the spectra can be from the molecular stretching, vibration, and bending. These peaks of the same chemical moiety can help with confirmation. Similarly the metal hydroxides, sulfates or sulfites, phosphates, carbonates, and chlorates can also be observed. For example, in clays, OH stretching modes can occur in the region of 3400–3750 cm^{-1}; metal-OH bending can occur in the range of 650–950 cm^{-1}. Si–O and Al–O stretching can be in the range 700–1200 cm^{-1} while bending of these can be in the low frequency range of 150–600 cm^{-1} (Schroder 2002). Often, the overlap of these absorption or transmission frequencies can be resolved by analyzing the stretching, vibration, and bending frequencies. Figure 13 shows the IR spectra of initial materials (before hydration) of Rapid Set (“RS-0”) and Utility Fill (“UF-0”).

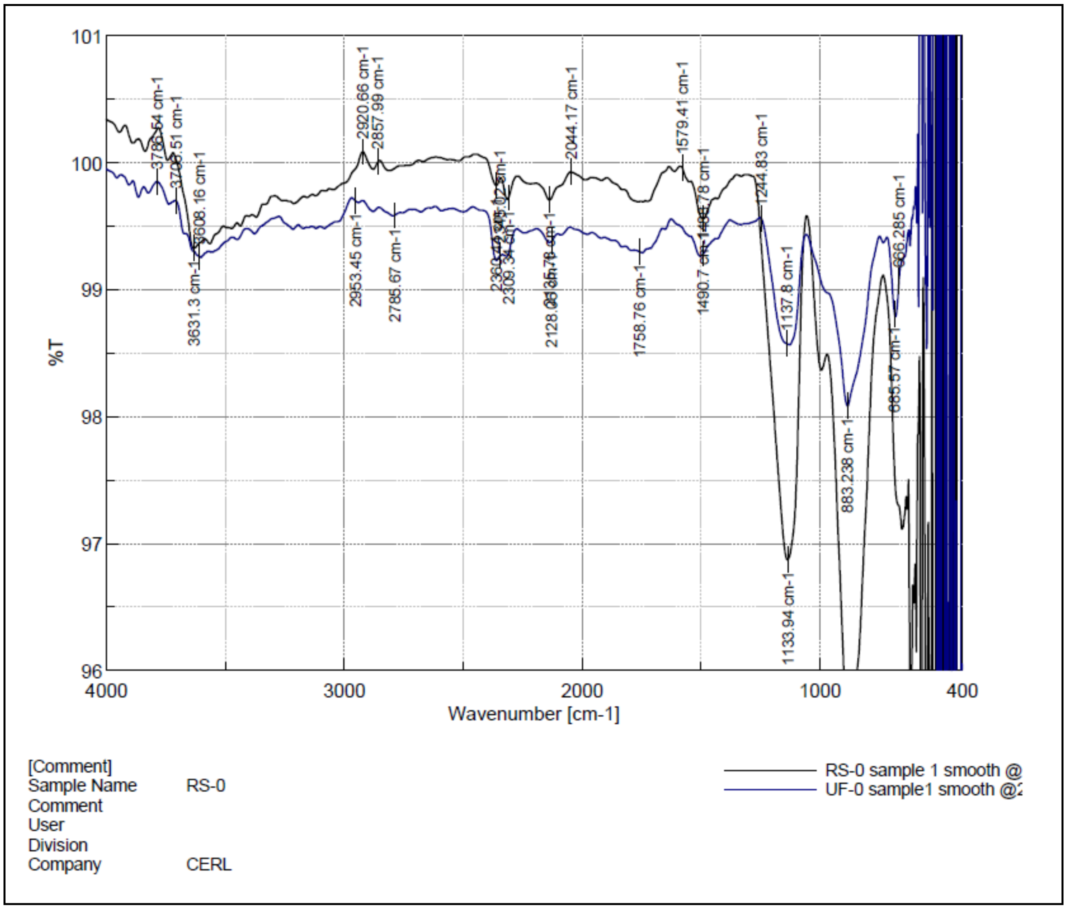


Figure 13. FTIR spectra comparison of Rapid Set Concrete Mix (“RS-0”) and Utility Fill concrete mix (“UF-0”) before hydration.

These mixes are chemically similar, but certain functional groups at 1133, 1000, 883, and 685 cm^{-1} give distinct variation in properties. The stretching hydroxyl (OH) groups in the range of 3500–4000 cm^{-1} are typically associated with silicon (Si) and aluminum (Al). The peaks at 3608 and 3633 can be assigned to Bassanite hydroxyls. The specific peak present in Rapid Set, for example at 1000 cm^{-1}, can be attributed to calcium sulfate. The peak at 1133 can be due to sulfate (Ylmen et al. 2009). Observation of changes in these peaks with hydration and as a function of setting time and strength would help improve formulations and cementing process.

Figure 14 shows the FTIR spectra of the Rapid Set material before and after hydration. The specific peaks at wave numbers 1100 and 783 cm^{-1} disappear after hydration. Also, no major increase in OH peaks at about 3600 cm^{-1} shows that no free moisture is available, perhaps indicating that all the water added is bound. Peaks at 1500 and 2140 either disappear or appear at reduced intensity after hydration. Several other peaks show the chemical functional groups that exist in the matrix. Disappearance of peak at 883 cm^{-1} indicates carbonate reactions and the involvement of carbon dioxide.

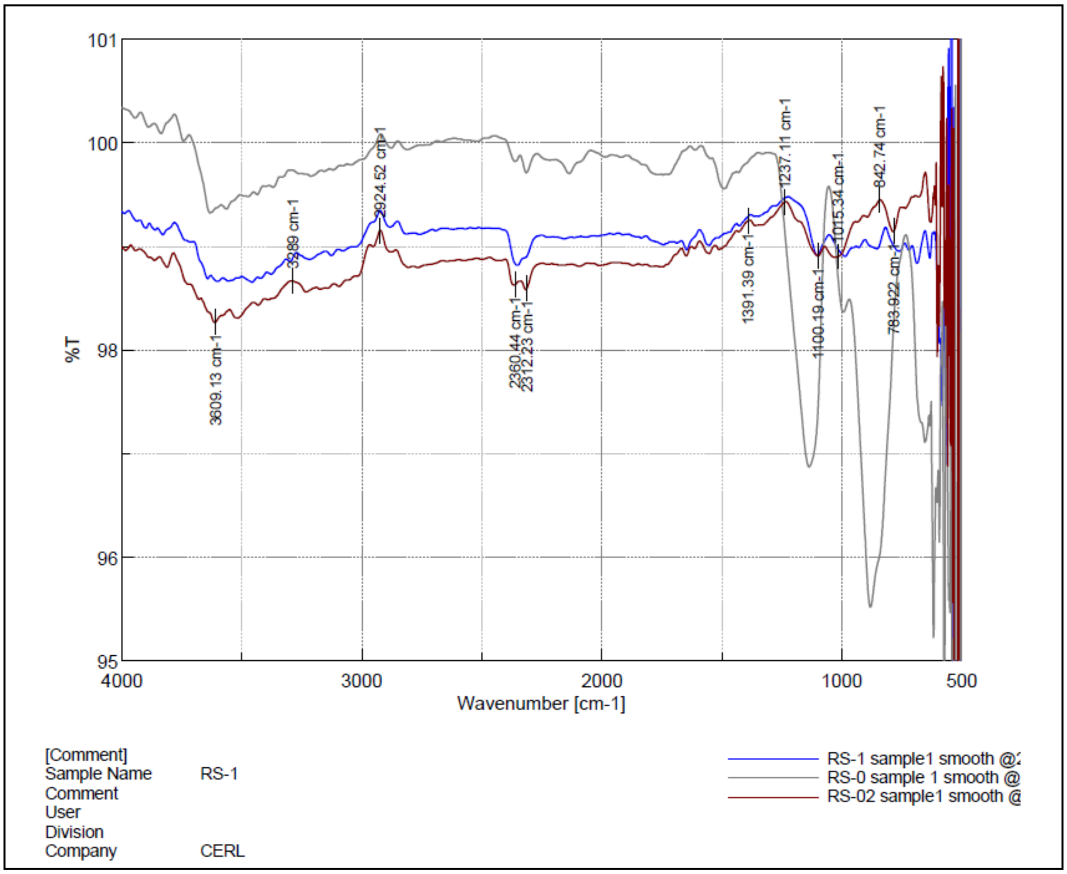


Figure 14. FTIR spectra of Rapid Set Concrete Mix before (“RS-0”) and after hydration (“RS-1” and “RS-2”).

Figure 15 shows the FTIR spectra of the Utility Fill material before and after hydration. The specific peaks at wave numbers approximately 1100 and 879 cm^{-1} appear before hydration. However, the after-hydration disappearance is inconsistent in sample RS-1 and RS-2. These peaks need further investigation to identify variations in the hydration process. In both the hydrated samples, there is an increase in hydroxyl groups at about 3450–3500 cm^{-1}. This hydroxyl stretching in association with the peaks in the range of 1100 to 1250 cm^{-1} indicate levels of water saturation and polymerization of silicate compounds in Rapid Fill. The peaks at about 2300–2370 cm^{-1} indicate the formation of sodium aluminosilicate compounds (Efimov and Pogareva 2000).

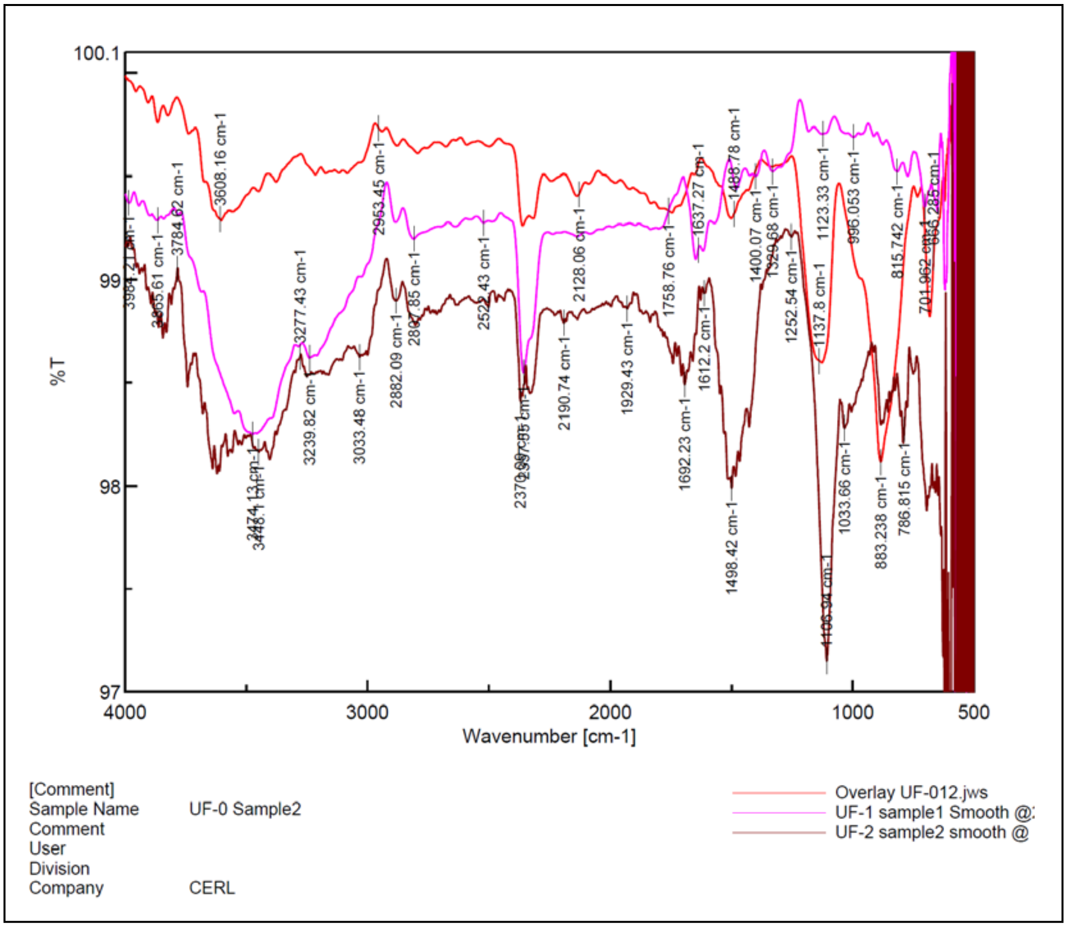


Figure 15. FTIR spectra of Utility Fill Concrete Mix before (“UF-0”) and after hydration (“UF-1” and “UF-2”).

Figure 16 shows IR spectra of Rapid Set (“RS-0”), Aluminum Sulfate, and Rapid Set after hydration along including aluminum sulfate (“CTS-RS-aluminum sulfate”). The significant observation is the presence of sulfate ions in the frequency range of 1100–1150 cm^{-1}, which is expected. It can also be noted that the presence of a hydroxyl peak at 3459 cm^{-1} indicates that with the addition of the aluminum sulfate admixture, there are more free hydroxyls (or water molecules).

A detailed IR study with the presence of admixtures is desirable and would help identify the effects of adding a specific admixture.

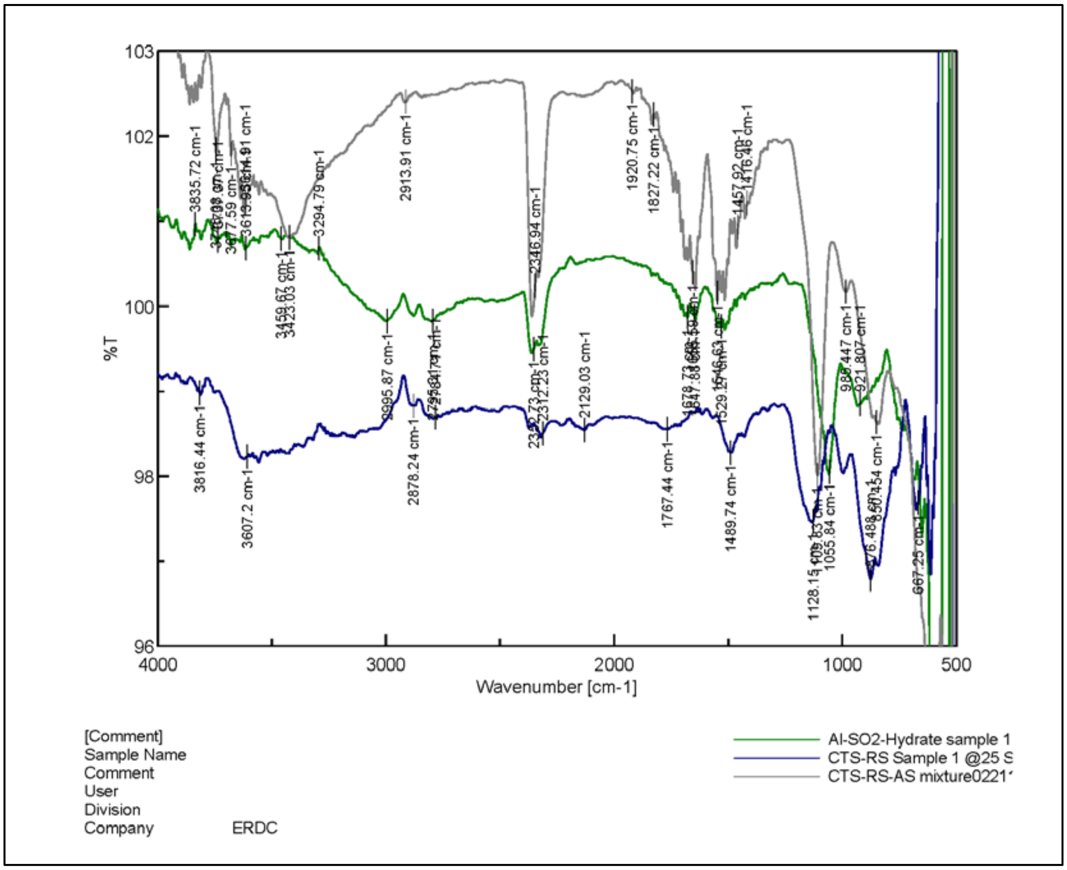


Figure 16. FTIR spectra of Rapid Set Concrete Mix ("RS-0"), aluminum sulfate and RS-0, and aluminum sulfate mixture.

4.4.3 Thermal properties

4.4.3.1 Isothermal calorimetry—early-age hydration reactions

Isothermal calorimetry was used to monitor early-age hydration reactions in the cementitious material extracted from Rapid Set and Utility Fill materials. Figure 17 shows normalized heat flow curves, obtained using isothermal calorimetry, for Rapid Set and Utility Fill materials with water and calcium chloride and aluminum sulfate accelerating admixtures. The kinetics of early-age reactions varied significantly depending on the materials and solution used. In the case of the Rapid Cement when mixed with water, we observed two peaks. The initial peak was associated with the wetting of the cement, and initial dissolution followed by a secondary hydration peak likely associated with the formation of ettringite. When we used aluminum sulfate, hydration reactions accelerated significantly, followed by continued hydration at rates similar to those when only water was present. When we used calcium chloride, initial wetting heats were similar to water alone. By early-age, hydration was inhibited significantly when compared with water alone, followed by an increase in heat flow associated with continued hydration beyond 1 hr. The behavior of the Utility Fill material was significantly different with a reduced heat associated with the wetting and hydration peak. We observed a third hydration peak in Utility Fill, at an approximate duration of 5 hr, that is likely associated with hydration of C_3S observed by XRD to be present in the Utility Fill material. Total normalized heats generated over the 6 hr test duration of each material were calculated by integrating the area under each calorimetry curve and are provided in Table 9.

These results confirm that the total heat generated by each cement and accelerating admixture combination is similar. However, changes in chemistry between the Utility Fill and Rapid Set materials and the various accelerating admixtures investigated in combination with the Rapid Set material did have a significant impact on reaction kinetics measured by isothermal calorimetry.

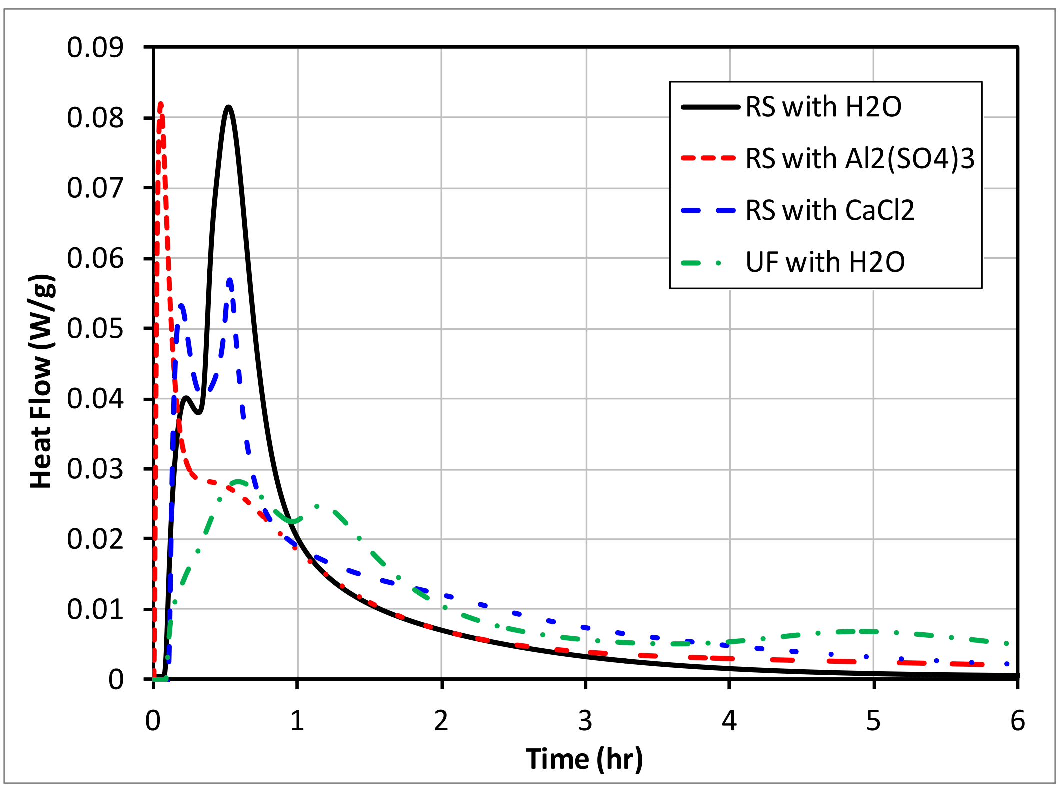


Figure 17. Normalized heat flow curves obtained using isothermal calorimetry at 23°C.

Table 9. Normalized heat generated over 6 hr test duration.

Material	Integrated Heat Over 6 hr (J/g)
RS with H_2O	214.2
UF with H_2O	225.1
RS with $CaCl_2$	248.6
RS with $Al_2(SO_4)_3$	198.8

4.4.3.2 Thermogravimetric analysis

Results of thermogravimetric analysis (TGA) are presented in Figures 18 through 21. The data provide a fingerprint of the materials before and after the hydration reactions of the two cements. The data show the weight loss as a function of temperature. Additional thermograms of the samples with admixtures would help comment on how the admixtures affect the chemical bonding and the mechanical properties. The weight loss over the entire temperature range for Rapid Set is about 13% (14.8%–1.8%) while it is about 9.6 % (17.4–7.8%) for Utility Fill. The heating rate is about 10°C/min in a nitrogen atmosphere at a flow rate of 100 mL/min.

The thermogram in Figure 18 shows minor loss of physically adsorbed moisture in the Rapid Set material prior to hydration. Figure 19 presents the thermogram obtained following hydration of the Rapid Set material with water. A clear mass loss associated with a loss of free moisture and dehydration of ettringite phases present in the hydrated material occurs in the range of 100°C to 120°C. Following this mass loss, we observed a gradual reduction in mass that is likely associated with more tightly bound moisture. Perhaps samples with admixtures will be different and will provide further information on how they interact with the cement matrix.

Figures 20 and 21 present thermograms of the Utility Fill materials before and after hydration, respectively. Similar to the Rapid Set material, we observed in the Utility Fill material prior to hydration a minor mass loss associated with loss of free moisture. Following hydration, mass loss of approximately 5 %, which is associated with loss of free moisture and dehydration of ettringite and other hydrates present in the hydrated microstructure, was observed in the temperature range of 100°C to 120°C.

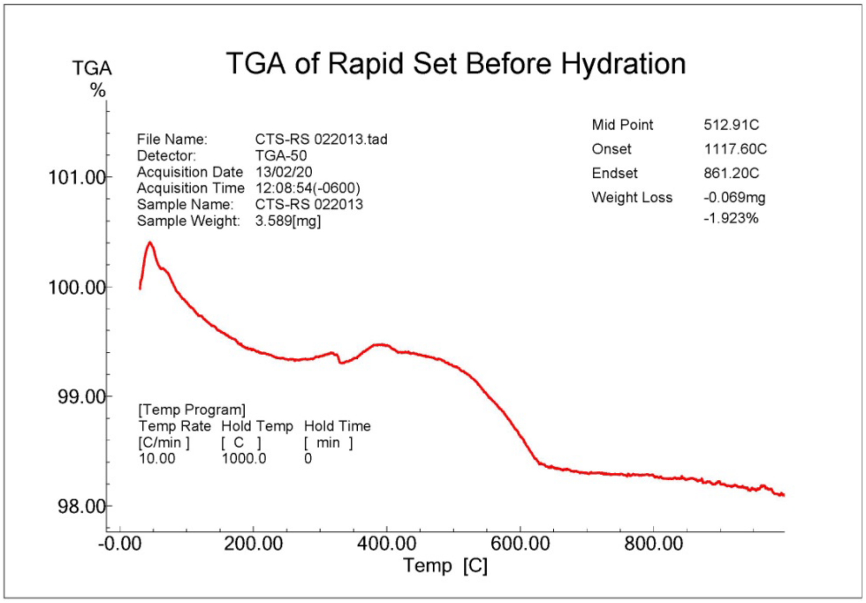


Figure 18. Thermogram of Rapid Set cement mixture before hydration.

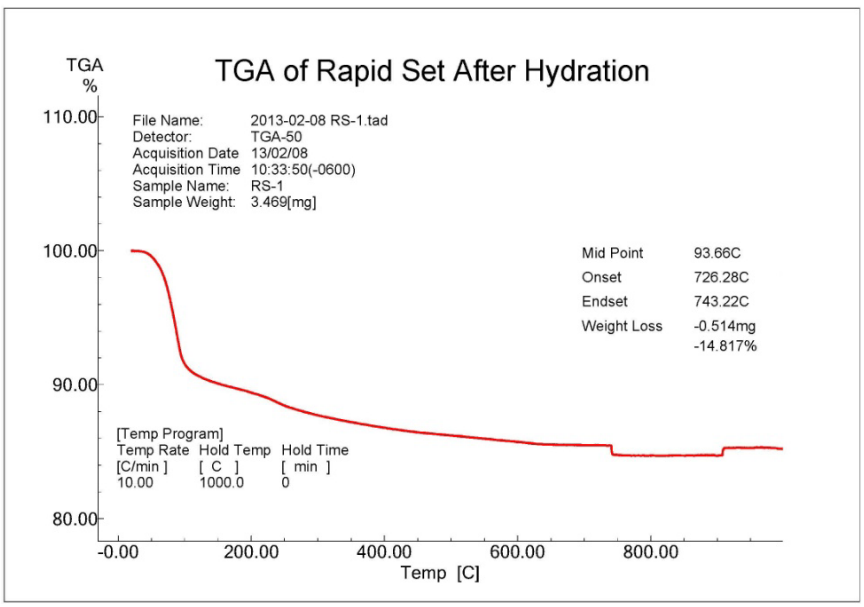


Figure 19. Thermogram of Rapid Set cement mixture after hydration.

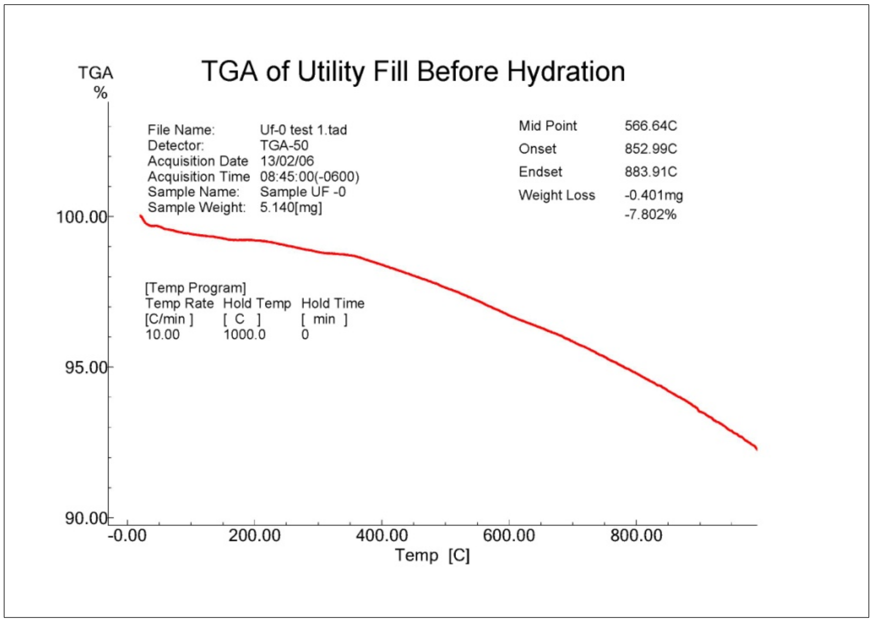


Figure 20. Thermogram of Utility Fill cement mixture before hydration.

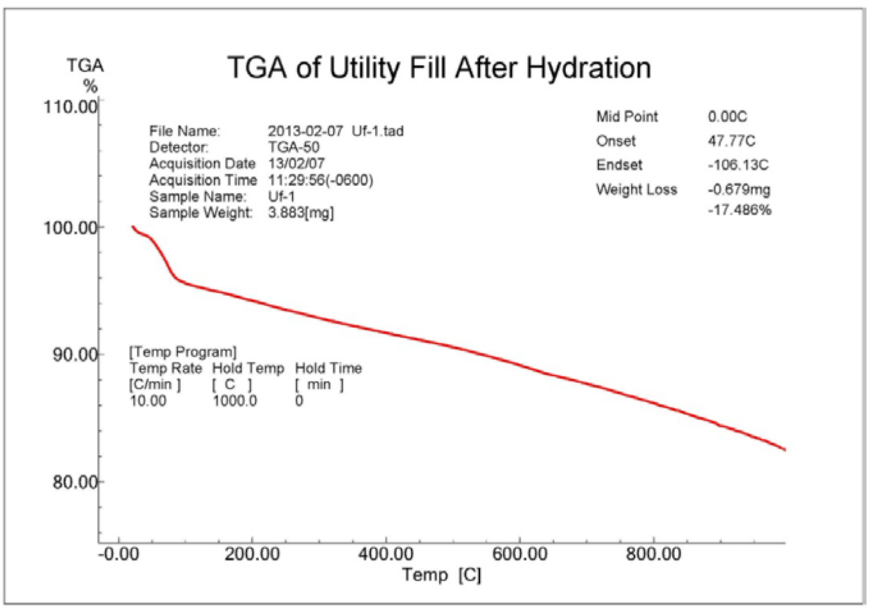


Figure 21. Thermogram of Utility Fill cement mixture after hydration.

4.5 Conclusions from the materials analyses

We can make many conclusions based on the analyses of the Rapid Set and Utility Fill materials and of various admixture. The key findings were as follows:

- XRD and XRF analysis confirmed that the both Rapid Set and Utility Fill materials are composed largely of CSA cements. This finding was also confirmed by SEM imaging of the hydrated microstructure, which were dominated by ettringite and calcium sulfate phases typically associated with the hydration of CSA cements. These results have implications in that many admixtures typically used for Portland cement-based concretes may not be applicable with CSA cements.
- SEM imaging of the composite obtained when Rapid Set and Utility Fill materials were hydrated with water alone and with calcium chloride and aluminum sulfate admixtures showed large changes in microstructure. When water alone was used, both Rapid Set and Utility Fill microstructures looked typical of CSA cements with a dominance of ettringite along with other calcium sulfate phases. When aluminum sulfate was used, the microstructure appeared to become more dense with additional gel-like binding phases between individual ettringite needles. When calcium chloride was used, the microstructure was less dense and less interlocked as the aspect ratio of phases was decreased.
- Isothermal calorimetry confirmed the effectiveness of aluminum sulfate and the poor performance of calcium chloride. When aluminum sulfate was present, the hydration peak was accelerated into the range of wetting of the cement, resulting in an almost instantaneous activation of the hydration process. When calcium chloride was present, the hydration peak was suppressed; and most early-age heat generation was associated with the wetting peak followed by slow hydration.
- FTIR spectroscopy showed changes in the chemical interactions present before and after hydration. However, additional work will be necessary to correlate these changes with admixtures used and with macro-scale material performance.
- Thermogravimetric analysis showed minimal free moisture in the as-received Rapid Set and Utility Fill materials prior to hydration. Following hydration, mass losses at 100°C to 120°C were observed, which are associated with the loss of free moisture and the dehydration of ettringite phases. These results are consistent with a CSA cementitious material composition.

5 Results and Discussion

5.1 Introduction

Appendix A (Tables A1–A7) includes all data for admixtures tested individually or in combination during each phase. Rather than discuss each table in detail, they are summarized in the tables and graphs that follow and referenced, as necessary, in the text below. The various admixtures and their combinations will be referred to in tables and in figures according to Table 10.

Table 10. Admixtures used throughout testing.

Admixture	Abbreviation*	Chemical Formula
Aluminum Sulfate (hydrate)	AS	$Al_2S_3O_{12}.xH_2O$; x = 12–14
Calcium Chloride	CC	$CaCl_2$
Calcium Nitrate	CN	$Ca(NO_3)_2$
Calcium Sulfate (hemi-hydrate)	CS	$CaSO_4.5H_2O$
Cane Sugar (granulated)	Sug	$C_{12}H_{22}O_{11}$
Glenium 7500 water-reducer	Gle	unknown (COTS† product)
Pozzutec 20+ accelerator (aluminum sulfate)	Poz	unknown (COTS product)
Sodium Nitrate	SN	$NaNO_2$
Sodium Sulfate	SS	Na_2SO_4

* These abbreviations are used in the tables in this section and in Appendix A

†Commercial off-the-shelf

5.2 Aluminum sulfate Rapid Set test phase

Previously, limited GSL research demonstrated that aluminum sulfate strongly accelerated the hydration process for the type III cement in the Rapid Set, though exact quantities required as a function of w/c and ambient, ground, and materials temperatures were unknown. The purpose of this test phase was to provide a higher degree of statistical certainty for recommended proportions of aluminum sulfate to be used given a variety of w/c and temperature factors. The secondary and broader goal was to determine one or two aluminum sulfate proportions that could span −10°C to 20°C ambient, ground, and materials' temperatures and still meet the set times and 2 hr UCS goals. Table 11 summarizes these recommended proportions. These recommendations are based directly on data in Appendix A or inferred from it (e.g., if aluminum sulfate 500 g failed to set at −10 °C, we inferred that aluminum sulfate 500 g fails to set at −15°C). Figure 22 shows the detailed performance of aluminum sulfate in terms of set time and 2 hr UCS, filtered by test temperature and aluminum sulfate proportion.

Table 11. Performance summary of aluminum sulfate admixture in Rapid Set Concrete Mix.

Aluminum Sulfate Amount Used		Temperatures Successful? Y/N/close/Unk (unknown)*,†,‡							
g aluminum sulfate per 60 lb dry Rapid Set	% aluminum sulfate by dry weight Rapid Set	−15°C	−10°C	−5°C	0°C	5°C	10°C	15°C	20°C
0	0.0%	N	N	N	N	N	N	Y	Y
100	0.4%	N	N	N	N	close	close	Y	Y
200	0.7%	N	N	N	Y	Y	Y	Unk	Unk
300	1.1%	N	close	Y	Y	Y	Y	N	N
400	1.5%	N	N	N	close	N	N	N	N
500	1.8%	N	N	N	N	N	N	N	N
600	2.2%	N	N	N	N	N	N	N	N
700	2.6%	N	N	N	N	N	N	N	N

* Success is defined as set time ≥ 15 min, 45 min, and 2hr UCS ≥ 2500 psi ; set is defined as ≥ 500 psi penetration resistance.

† Dry materials and ambient average temperatures at specified levels in chart; mixing water about 10°C; target slump = 4–6 in.; water quantities 7.5–9.0 lb per 60 lb dry Rapid Set (more water necessary as aluminum sulfate is added)

‡ Aluminum sulfate dissolved in mixing water and immediately mixed into Rapid Set mix

Not explicitly shown in Table 11 nor Figure 22 are the results variability as a function of w/c. While the results of set times and 2 hr UCS vary with w/c, the results shown are based on an average slump of 4–6 in., corresponding to a workability estimate of 4–6 (1 = unworkable, 10 = liquid pour). Because aluminum sulfate is hygroscopic, we added slightly higher amounts of water to each batch, with a rough trend of 0.25–5 lb additional water needed per 60 lb Rapid Set batch with each addition of 100 g of aluminum sulfate. Adding this additional water was necessary to maintain an average slump of 4–6 in. We should note that, at the extremes of successful performance for each row in Table 11 (for example: −10°C and +10°C for 300 g aluminum sulfate), w/c ratios that deviate from 4–6 in. slumps are likely to fail the set time and 2 hr UCS goals.

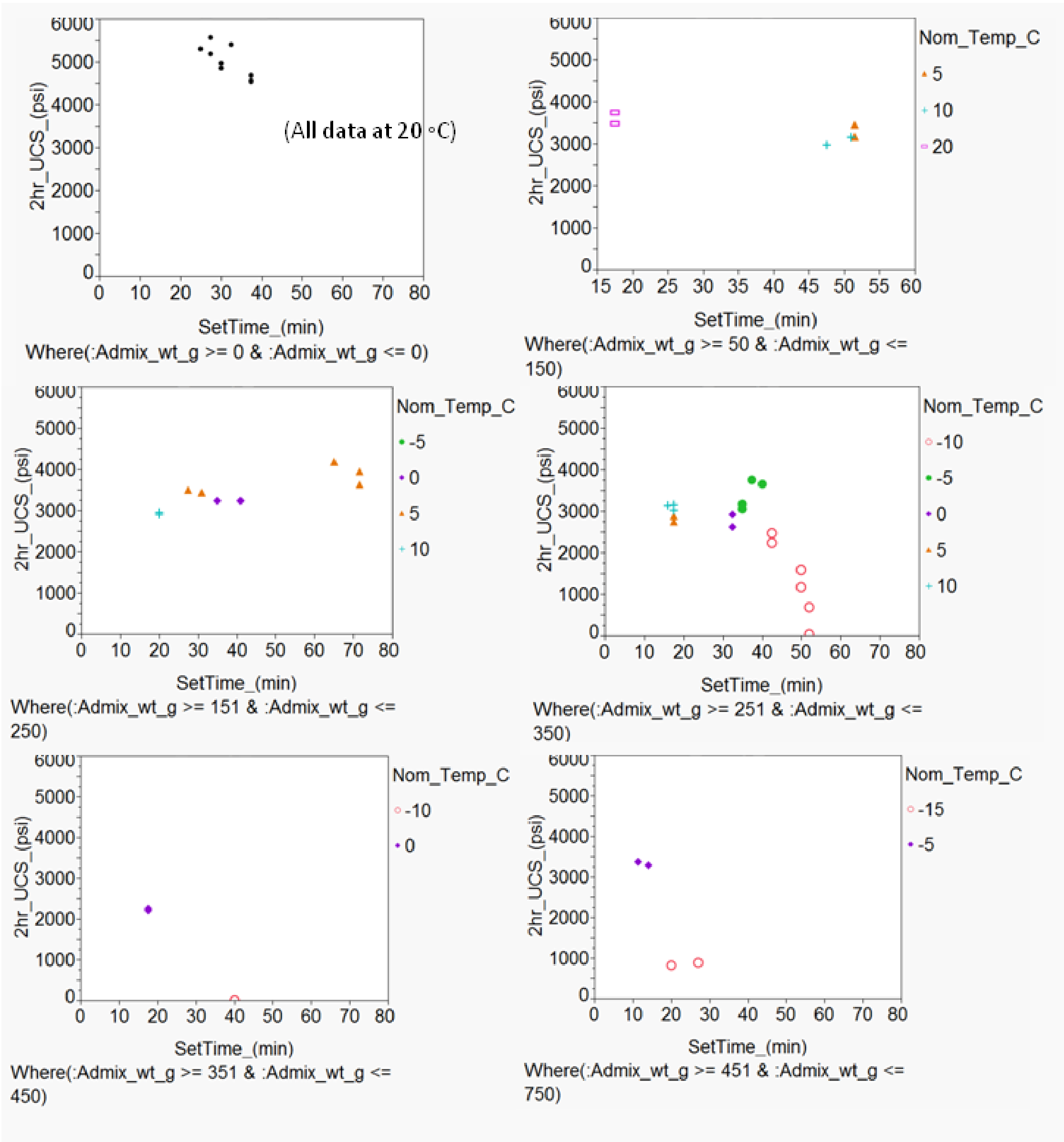
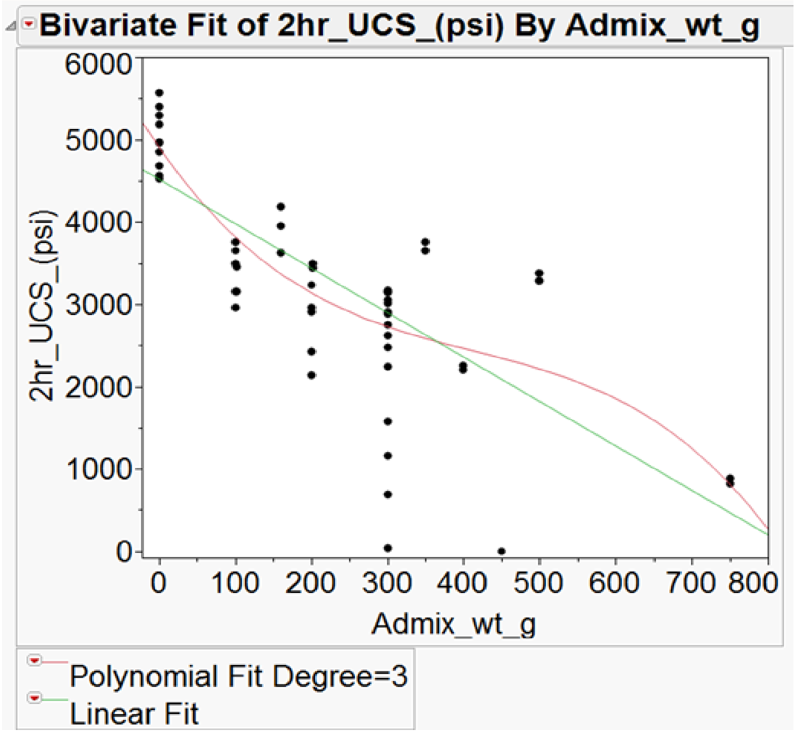


Figure 22. 2 hr UCS (psi) vs. SetTime (min) by Nom_Temp_C, filtered by different amounts of aluminum sulfate (g) used in Rapid Set Concrete Mix.

Table 11 demonstrates that using aluminum sulfate at higher dosage rates (>1.1% by weight of dry Rapid Set) tends to cause a "false set" due to two primary factors. First, the cement rapidly stiffens as the aluminum sulfate stores most of the available water. Then, the mixture hardens as high heat is generated during both the heat of dissolution into the mixing water and in the initial cement hydration process (of the remaining available water). These effects in turn result in an incomplete hydration process with compressive strengths much lower than the 2500 psi 2 hr UCS goal. Figure 23 demonstrates the negative correlation between the amount of aluminum sulfate used and 2 hr UCS and shows testing at all temperatures and w/c.



Summary of Fit (poly 3)	
RSquare	0.683082
RSquare Adj	0.6724
Root Mean Square Error	717.961
Mean of Response	3320.785
Observations (or Sum Wgts)	93

Summary of Fit (linear)	
RSquare	0.633201
RSquare Adj	0.62917
Root Mean Square Error	763.8639
Mean of Response	3320.785
Observations (or Sum Wgts)	93

Figure 23. Determining the correlation between 2 hr UCS and the amount of aluminum sulfate used (g) in Rapid Set Concrete Mix.

Results in this phase of testing demonstrate that aluminum sulfate, used in the right proportions within the right ambient, ground, and materials temperature ranges, is a suitable admixture for accelerating the hydration process of Rapid Set concrete at low temperatures. One should take care to avoid using too high proportions of aluminum sulfate as this has a negative effect on early (and assumed, though not demonstrated, ultimate) strength gain, lowers workability, and can cause either “false” or “flash sets” to occur.

5.3 Utility Fill and Rapid Set hot water test phase

The objective of the second task was to determine whether a suitable admixture could chemically heat (via exothermic reaction) the mixing water for use in both the Utility Fill and the hard cap to meet the time of set and 2 hr UCS goals (Rapid Set only). Any admixture added must provide this reaction initiation improvement without degrading the performance of either mixtures (set or UCS values, estimates for short-term durability, or other). The project manager and the sponsor (AFCEC) have deemed their approach to solving the performance issues at low temperatures lowest risk given tactical and practical short-term constraints with introducing any changes to the mixtures already procured and in use. In addition, the PM and sponsor have deemed the mechanical heating of the mixing water stored in the concrete equipment higher risk due to potentially permanent, invasive vehicle alteration issues, cost, and other potential issues. Solutions involving mechanical heating and additions to the dry materials were not explored in depth for these reasons.

To meet the objective of the second task, we conducted testing in two phases. First, we conducted a series of hot water tests for both the Utility Fill and the Rapid Set to identify the temperature ranges where hot water (whether mechanically or chemically heated) enabled successful times of set and strength gains. Tables 12 and 13 summarize results and recommendations for hot water usage for Utility Fill and Rapid Set, respectively. These recommendations are based directly on data in Appendix A (table A6) or inferred from it (e.g., because the Utility Fill failed to set with hot water at 40°C and an ambient materials temperature of −5°C, we inferred that the Utility Fill fails to set using <40°C water at a ≤−5°C ambient, materials temperatures).

Table 12. Utility Fill hot water test: performance summary of Utility Fill at specified ambient and dry materials temperatures using mixing water at specified temperatures. No admixtures added.

Ambient, Dry Materials Temp °C	Average Time of Set (min to reach 250 psi penetration resistance) per Water Temp (°C) in Below Row										
	100	90	80	70	60	50	40	30	20	10	5
20					6				9		14
10					8				23		28
5											
0					10				no set		
-5					15		frozen				
-10											
-15		frozen			frozen						

Meets time of set (15–30 min to reach 250 psi penetration resistance) requirement

Borderline meeting time of set requirement

Fails to meet time of set UCS requirement

Table 13. Rapid Set hot water test: performance summary of Rapid Set Concrete Mix at specified ambient and dry materials temperatures using mixing water at specified temperatures. No admixtures added.

Ambient, Dry Materials Temp °C	Average Time of Set (min to reach 500 psi penetration resistance); Average 2 hr UCS per Water Temp (°C) in Below Row:										
	100	90	80	70	60	50	40	30	20	10	5
20									35 ; 4840		
10					30 ; 4617				70 ; 3866		
5											
0		43 ; 4423			80 ; 3769						
-5		39 ; >3500									
-10											
-15											

meets time of set (15-45 min to reach 500 psi penetration resistance)and 2 hr UCS (>2500 psi) requirements

borderline meeting time of set and 2 hr UCS requirements

fails to meet time of set and 2 hr UCS requirements

The results in Tables 12 and 13 demonstrate the feasibility of using heated mixing water within certain temperature ranges for successful Utility Fill and Rapid Set performance. We used the following heuristic throughout the testing to estimate the minimum mixing water temperature required depending on the ambient or dry materials temperature:

$$T_{water_{min}} = \frac{W_{water} + W_{dry\ mix}}{W_{water}} x \ \ \min\{0 - \ T_{amb\&mat}, 0\} + \ 1$$

where

$T_{water_{min}}$ = the minimum temperature of the mixing water required for successful Utility Fill or Rapid Set performance, in °C,
W_{water} = the weight of the water required in the mix to achieve the desired slump,
$W_{dry\ mix}$ = the weight of the dry mix (Utility Fill or Rapid Set),
$T_{amb\&mat}$= the ambient and materials temperature.

The heuristic provided the test team with a lower bound for the water temperature by incorporating a rough estimate for the composite mixture temperature (once water was added) and the minimum temperature to raise the composite mixture to enable the hydration process. Because the ratio of the total weight to water weight in both mixtures was approximately 9 to 12:1, each degree difference between the mixture goal temperature and the ambient temperature required a minimum of 10°C higher water temperature.

Further research should be conducted to determine in more detail the optimal wet mixture composite temperature ranges suitable to meet the time of set and 2 hr UCS goals. This would then enable construction of a more thorough and reliable hot water model and would aid in planning future Utility Fill and Rapid Set low-temperature activities.

The high temperatures required for the large volumes of mixing water highlight the difficulty of chemically heating the water with known admixtures (using heat of dissolution; oxidation-reduction reactions, such as used in flameless water heaters in military rations heaters;* or other techniques) to achieve the ambient temperature ranges shown in Tables 12 and 13. In addition, the large volume of admixtures required to chemically heat the water would have to not interfere with the cement hydration process

* An example oxidation-reduction reaction that is used to reliably heat military rations ("Meal, Ready-to-Eat," or MREs) involves the generation of heat in an electron-transfer process called an oxidation-reduction reaction, where water oxidizes magnesium metal. For more information on this example reaction method, see HowStuffWorks (2013).

(by either storing most of the available water or acting as an retarding agent or inhibitor) nor cause short- or medium-term negative effects, such as increased concrete temperature expansion or other durability concerns, and would pose no significant safety hazards in use or in storage. For these reasons, we determined that mechanical heating is a more feasible method than admixtures to heat the mixing water to the temperature ranges specified in Tables 12 and 13. The admixture investigations section demonstrates this infeasibility by testing a variety of salts. See the recommendations section for a candidate method of employing the Utility Fill at low ambient and dry materials temperatures by using a mechanical heating solution.

5.4 Admixture investigations, Rapid Set

The purpose of the rapid set admixture investigations task was to improve the performance of the Rapid Set with the following constraints:

1. Hard cap time of set (time to reach 500 psi penetration resistance) min/max: [15 min, 45 min].
2. Temperature ranges suitability goal for new admixture: [−15°C, 10°C].
3. 2 hr UCS: ≥ 2500 psi.
4. Admixtures must be added to the water with no alterations to the Rapid Set dry mix.
5. Mixing water temperature: −5°C to 0°C for an extended period of time prior to start of mission. (Optional additional constraint to improve length of time water can sit in the mixing vehicle prior to conducting rapid runway repair mission.)

Note that solutions satisfying the fifth constraint would provide an improvement to the performance of the hard cap at cold temperatures using only an aluminum sulfate admixture because aluminum sulfate acts primarily as an accelerant to the hydration process and is a poor freezing point depressant. An aluminum sulfate and water solution close to 0°C for an extended period of time would exhibit significant icing and does not have a strong hydration accelerant effect when introduced to the Rapid Set dry mix.

Table 14 summarizes the performance of all admixtures used (alone or in combination) at a variety of ambient and mixing water temperatures. Admixtures used throughout this phase of investigations were determined as the most promising candidates for depressing the freezing point of the mixing water, accelerating the hydration process, and improving the w/c or overall cementitious content in the mix. See Section 3 for more information on each admixture and its corresponding properties.

Table 14. Admixture investigations summary, Rapid Set: performance summary of Rapid Set at specified ambient, dry materials temperatures when using mixing water solutions at specified temperatures and a variety of admixtures (alone and in combination).

Admixture	Ambient Temp (°C)	Solution Temp (°C) (just prior to mix UF)	Max 20 min Penetration Resistance (psi)	Max 45 min Penetration Resistance (psi)	2 hr UCS (psi)	Slump (in.)	Freezing Concerns? (Y/N/some)	Promising? (Y/N)
AS	−5	5−10	20	>800	3100	4	N	Y*
	−5	0	0	0	0	0	Y	N
CC	−5	0	0	0		6−7	N	N
CS	−5	0	16	32		6−7	Y	N
CC-AS	−5	0	40	40		5−6	Y	N
CC-CN	−5	-5	16	40		5−6	N	N
	−5	0	8	56		5−6	N	N
CC-Sug	−5	0	0	32		6−7	N	N
CC-Poz	−5	0	0	16		5−6	N	N
CN-Poz	−5	0	0	15		5−6	N	N

* Best performance shown in table for the range of admixture proportions investigated. For specific admixture proportions investigated and all related data, see Appendix A.

While some of the admixture combinations allowed the Rapid Set to set and to reach 2500 psi unconfined strength, none of the admixture combinations were able to meet the required timeframes for set and strength gain when the water solution was cooled between −5°C and 0°C prior to mixing with the Rapid Set. Consequently, aluminum sulfate at a variety of cold ambient and dry materials temperatures with a minimum mixing solution temperature of 5°C provided the only suitable performance for the Rapid Set. Refer to Table 11 for the recommended aluminum sulfate proportions as a function of ambient and dry mix temperatures.

5.5 Admixture investigations, Utility Fill

The purpose of the Utility Fill admixture investigations task was to improve the performance of the Utility Fill with the following constraints:

1. Utility Fill time of set (time to reach ≥250 psi penetration resistance) min/max: [15 min, 30 min].
2. Temperature ranges suitability goal for new admixture: [-15°C, 10°C];
3. Admixtures must be added to the water with no alterations to the Utility Fill dry mix.

Penetration resistance increased for all samples when the available water froze (excluding samples that successfully depressed the water freezing point), which could easily be mischaracterized as an initial set. All promising admixture samples were therefore screened with a 2 hr UCS test to ensure a minimal amount of compressive strength gain (about 100 psi). We deemed predominantly or completely frozen any samples with less than 100 psi UCS results and discarded them. The primary concern with freezing of the Utility Fill layer is that the Utility Fill will not have a minimum bearing pressure even when confined in a small hole (approximately 8 × 8 × 3 ft depth), causing the hard cap layer to fail under the large (5000 psi) anticipated vehicle loadings. In addition, substantial freezing and thawing of the Utility Fill layer poses a large risk for heaving with a low number of freeze–thaw cycles. While the Utility Fill may spread the high vehicle loadings sufficiently when partially frozen because of confinement in a relatively small area, performance may suffer when the ground thaws or after several freeze–thaw cycles. See the recommendations section for additional constraints to be explored to mitigate durability concerns of the Utility Fill while not imposing an excessive requirement for unconfined strength.

Table 15 summarizes the performance of all admixtures used (alone or in combination) at a variety of ambient and mixing water temperatures. Admixtures used throughout this phase of investigations were determined as the most promising candidates for depressing the freezing point of the mixing water, accelerating the hydration process, and improving the w/c or overall cementitious content in the mix. See Section 3 for more information on each admixture and its corresponding properties.

We did not discover any admixtures that could produce results similar to the control at 20°C ambient temperature and 5°C–10°C mixing water temperature. However, one admixture type (single or combination) that performed slightly better than the control tests at −5°C ambient and dry materials temperature and 60°C–80°C mixing water temperature was aluminum sulfate, with the best performance using aluminum sulfate 8%

by weight in water solution (results for aluminum sulfate 8% shown in table 15. The aluminum sulfate admixture exhibited the same 30 and 60 min penetration resistance values as the control, with a slightly higher 2 hr UCS reading. Additional testing should be conducted to determine whether this improvement is statistically significant and whether the 2 hr UCS for both the control and the aluminum sulfate admixture at solution temperature 80°C is sufficiently durable.

Table 15. Admixture Investigations Summary, Utility Fill: performance summary of Utility Fill at specified ambient, dry materials temperatures when using mixing water solutions at specified temperatures and a variety of admixtures (alone and in combination).

Admixture	Ambient/ Dry Materials Temp (°C)	Solution Temp (°C) (just prior to mix UF)	Max 30 min Penetration Resistance (psi)*	Max 60 min Penetration Resistance (psi)*	2 hr UCS (psi)	Slump (in.)	Freezing Concerns? (Y/N/some)	Promising? (Y/N)
AS	−5	5–10	0	0	0	8	Y	N
	−5	60	240	640	0	10	Y	N
	−5	80	520	800	98	8	some	Y*
CC	−5	10	0	176	0	8	Y	N
	−5	60	208	488	0	10	Y	N
	−5	80	224	520	0	9	Y	N
Gle	−5	60	144	360	0	10	Y	N
	−5	80	384	760	33	9	some	N
SN	−5	5–10	0	0	0	9	N	N
SS	−5	5–10	0	0	0	9	N	N
CC-CN	−5	5–10	0	0	0	9	N	N
CC-SS	−5	5–10	0	112	0	9	N	N
AS-CN	−5	5–10	0	40	0	8	N	N
AS-SS	−5	5–10	0	24	0	8	N	N
AS-SN	−5	5–10	0	32	0	8	N	N
Control (no admix)	−5	80	520	800	74	9	some	Y
Control (no admix)	20	10	>800	>800	507	9	n/a	n/a

* Best performance shown in table for the range of admixture proportions investigated. For specific admixture proportions investigated and all related data, see Appendix A.

We discovered no admixtures that could provide suitable performance when the mixing water was in the range of 0°C–10°C. Because of this, our best demonstrated performance for the Utility Fill at cold temperatures required manual heating of the mixing water (or aluminum sulfate 8%–

water solution) to 60°C–80°C to enable the Utility Fill to set in 15–30 min without freezing. See the recommendations section for additional future testing to improve this performance and to investigate durability concerns. It also includes other recommendations to successfully heat the Utility Fill mixing water in an operational setting.

5.6 Models for prediction and results repeatability

We fit various stepwise regression models on our data in task 3 (aluminum sulfate Rapid Set testing) using standard statistical software (JMP [SAS Institute Inc. 2012]) to quantify which effects variables exert the greatest influence on our dependent variable (set time or 2 hr UCS) and to account for as much variance as possible in our overall models. Table 17 summarizes prediction results by using all data from task 3, and Table 16 summarizes prediction results by using only a portion of data from task 3 (all testing conducted with the first shipment of Rapid Set).

Table 16. Prediction results of select stepwise regression models for the first round of aluminum sulfate (task 3) testing (first 57 tests with the first shipment of Rapid Set product), using Aikake Information Criterion (AIC) stopping criterion.

Model #	Predict Variable	Data Used	Input Factors	Train			Test		All Data	
				Factors Chosen (within *a* = .01)	Adj R^{2}*	Root Mean Squared Error (RMSE)	Adj R^2	RMSE	Adj R^2	RMSE
1	Set time (min)	all (includes incomplete data)	admix (quantity); temp; water; admix × temp; admix × water; temp × water	admix; temp; water; admix × temp	0.428	15.5	0.389	13.9	0.444	15.2
2	Set time (min)	all (excludes tests 7, 12–14, 17–22)	admix (quantity); temp; water; admix × temp; admix × water; temp × water	admix; temp; water	0.767	7.5	0.63	10.1	0.715	8.4

* Adjusted coefficient of determination

Table 17. Prediction results of select stepwise regression models for all aluminum sulfate (task 3) Rapid Set testing, using AIC stopping criterion.

Model #	Predict Variable	Data Used	Input Factors	Train: Factors Chosen (within a=.05)	Train: Adj R^2	Train: RMSE	Test: Adj R^2	Test: RMSE	All Data: Adj R^2	All Data: RMSE
1	Set time (min)	task 3 (all)	admix (quantity); temp; water; admix × temp; admix × water; temp × water	admix; temp; admix × temp	0.71	8.6	0.43	11.5	0.68	9.0
2	Set time (min)	task 3 (all except tests 12–14)	admix (quantity); temp; water; admix × temp; admix × water; temp × water	admix; temp	0.587	9.4	0.42	12	0.65	9.4
3	Set time (min)	task 3 (all except cook's distance outliers_1)	admix (quantity); temp; water; admix × temp; admix × water; temp × water	admix; temp; admix × temp	0.84	5.9	0.43	11.5	0.68	9.0
4	Set time (min)	task 3 (all except cook's distance outliers_2)	admix (quantity); temp; water; admix × temp; admix × water; temp × water	admix; temp	0.86	6.0	0.45	11.3	0.65	9.4
5	Set time (min)	task 3 (all except tests 12–14, and 17–21)	admix (quantity); temp; water; admix × temp; admix × water; temp × water	admix; temp; water	0.767	7.6	0.48	11.0	0.66	9.3

All models in Table 17 are color coded green, yellow, or red in terms of overall efficacy in both prediction ability on a blind data subset (random split: 75% train, 25% test) as measured by the test RMSE and in its ability to account for explainable variance as described by the adjusted coefficient of determination (adj R^2). We first observe that, if only modeling the first uniform batch of materials used in testing (Table 16, we can explain at most approximately 71% of the overall data variance (max adj R^2 .715) or 63% of the data variance in the blind data subset. This in turn leads to a prediction ability of set time (our dependent variable) within approximately 8.4 and 10.1 min for the overall and blind data (subset data only), respectively. However, if we model the entire task 3 data set (Table 17), we can explain at most approximately 65%–68% of the overall data variance (max adj R^2 .65–.68), and 42%–48% of the data variance in the blind data subset. This in turn leads to a prediction ability of set time within approximately 9.0–9.3 min and 11–11.5 min for the overall and blind data (all data), respectively. We conclude that, because we cannot control the contents of the Rapid Set from batch to batch when using less than a 2000 lb batch, our ability to model and predict results with each batch is degraded. However, when we control the ratio of fines to course aggregates in each batch, we can limit this variability and still produce results that are repeatable though slightly degraded.

Next, we note the importance of removing outlier points as we compare model results in both tables. Our ability to account for the data variance dramatically improves between models 1 and 2 in Table 16, and to a lesser extent in Table 17.

Finally, we note that several models produce suitable prediction performance using similar factors. All three “best” models shared the following factors: time, admixture proportion used, nominal temperature, and water content (w/c). One of the possible two-way interaction terms was also statistically relevant in some of the best models: water × temp. It is likely that this two-way interaction term and possible others would have had a larger statistical effect if all Rapid Set samples were more closely comparable. However, because the test team was unable to tightly control the cement:sand:course aggregates, this variability from batch to batch masked lesser variations that may have been otherwise accounted for with two-way interaction terms.

We now compare select models’ prediction abilities graphically to identify potential problems in various models, such as non-normality in error terms, and other undesirable effects, such as the inability to predict suitably in certain ranges rather than overall average prediction ability. To do this, we use each model’s estimates for factors used and coefficient terms to predict penetration resistance on our withheld blind test data subset (as well as record results from the model’s training data subset). We then order all data by actual penetration resistance observed from lowest to highest, as shown in Figures 24 and 25.

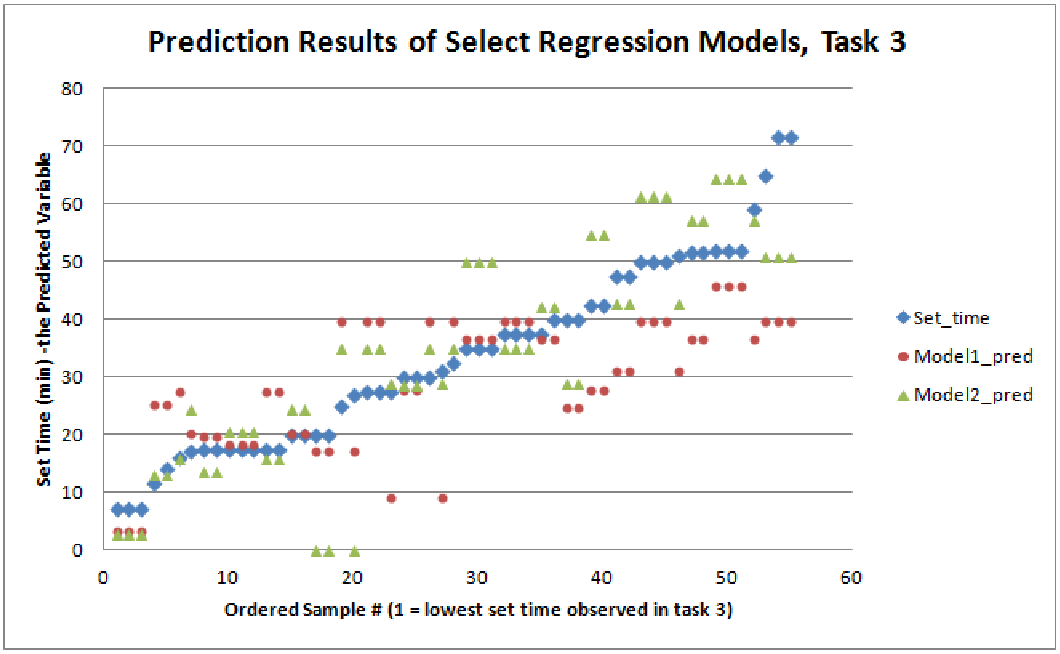


Figure 24. Prediction results of select stepwise regression models for the first round of aluminum sulfate (task 3) testing (e.g., 57 tests with first shipment of Rapid Set product), using AIC stopping criterion. Data are ordered from smallest to largest by actual set time observed and plotted as set time versus ordered sample number (sample 1 is the fastest set time at 7 min; sample 63 is slowest at 72 min).

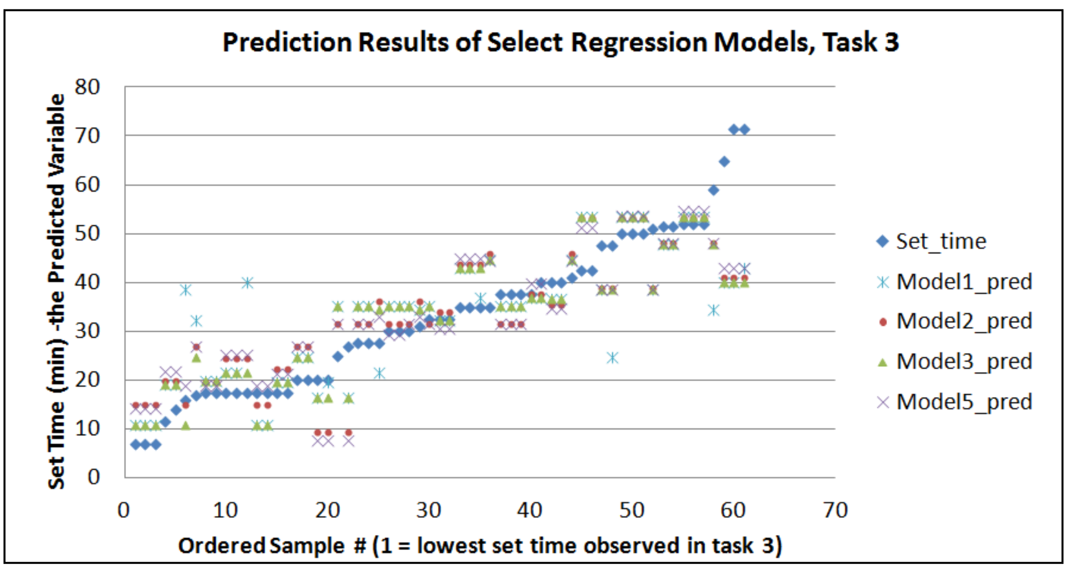


Figure 25. Prediction results of select stepwise regression models for all aluminum sulfate (task 3) testing, using AIC stopping criterion. Data are ordered from smallest to largest by actual set time observed and plotted as set time versus ordered sample number (sample 1 is the fastest set time at 7 min; sample 63 is slowest at 72 min).

The vertical distance of each predicted model value to the actual penetration resistance value (blue diamonds) represents the magnitude of each error term because a prediction will lie directly on the blue diamonds if there were no error between the predicted and actual values.

We first observe that model 2 in Figure 24 (data subset task 3) has predicted values more normally scattered about the actual values than the best models in Figure 25 (all data task 3); or in other words, the first model exhibits fewer non-normality concerns. Both models in Figure 24 predict 20–30 min lower than actual set times when set times are greater than 55 min. While this is clear evidence of a violation of our normality assumption when constructing regression models, the amount is low enough to be acceptable.

We also observe the importance of removing outlier points as we compare model results in both figures. While Tables 16 and 17 demonstrated the importance of removing outlier points to improve our overall model RMSE and adjusted variance, removing outliers is also important for lowering the maximum variance from predicted values. Model 1 shown in Figure 24, though it demonstrated similar RMSE and adjusted variance in Table 17 to the models 2–5 shown in Figure 25, exhibits a tendency to have large variance from the actual set time as noted in sample numbers 6, 7, 12, 48, and 58.

We conclude that our best models shared the following effects variables: time, admixture (aluminum sulfate) proportion used, nominal temperature, and water content (w/c ratio). In addition, if Rapid Set samples were able to be more tightly controlled in future testing, two-way interaction terms to include water × temp (and possibly others) should be considered. We have demonstrated that aluminum sulfate can be used in future testing with a significant amount of reliability around the intended set times recommended in Table 11, given a fixed w/c and ambient, dry materials and water temperatures.

6 Conclusions

ERDC tested and evaluated a variety of methods to improve the cold weather performance of a two-step solution currently in limited use for the purpose of expedient runway repair by the Air Force. The two-step solution involves placing a flowable fill (Utility Fill), which quickly hardens in approximately 30 min, in the majority of the crater; the repair team then places a Rapid Set concrete as the top layer, which allows for heavy runway traffic (2500 psi) within approximately 45 additional minutes. Because both the Utility Fill and Rapid Set exhibit issues setting and reaching design strengths when the temperature is below 10°C, we explored a variety of methods to improve the performance of both materials at near- and sub-freezing temperatures (ambient, ground, and materials' temperatures).

The first investigation involved improving the Rapid Set performance in temperature ranges of −10°C to 10°C by using aluminum sulfate hydrate (aluminum sulfate). We demonstrated that aluminum sulfate provided suitable performance for both set times and 2 hr UCS; Table 11 details proportions for water content and aluminum sulfate by weight of dry Rapid Set. The set times for all aluminum sulfate testing proved to be predictable with an average error of 9 min when using the following effects variables: water content, ambient temperature (when temperature of the dry materials is approximately the same as ambient temperature), quantity of aluminum sulfate used, and an optional 2-way interaction term water × temperature. This error could be improved in the future by having tighter controls on the Rapid Set proportions per batch used because the batches varied considerably due to retrieving them from a 2000 lb sack of the cement, sand, and course aggregate materials.

The next investigation determined the ranges of hot water suitable for set times and strength gain requirements for the Utility Fill and Rapid Set using no admixtures. Hot water was a suitable method for obtaining successful results for both materials, and tables 12 and 13 summarize these results. This discovery allows for two options for successful emplacement of the Rapid Set materials: use of aluminum sulfate or mechanical heating of the mixing water (using no admixtures). Because the laboratory testing may exhibit different heat transfer properties than a realistic operational environment, the most promising temperature ranges for ambient, materials, and mixing water should be tested in an operational environment using realistically-sized craters (see recommendations section).

The final investigation explored a variety of admixtures (alone and in combination) that may improve the performance of both the Utility Fill and Rapid Set materials at near- and sub-freezing temperatures. The primary constraint is that any admixtures used must be soluble in the mixing water. We identified a small list of admixtures to explore from a large list of potential admixtures previously identified in historical investigations to provide one of three performance characteristics (depressing the freezing point of the mixing water, accelerating the hydration process, or lowering the w/c, thereby increasing the total cementitious content). We found no admixtures that demonstrated better performance than the aluminum sulfate in the Rapid Set, which produced reliable results from −5°C to 10°C, meeting all objectives and constraints. We found no admixtures that demonstrated significantly better performance than hot water for the Utility Fill in temperature ranges −5°C to 10°C though early results indicate that a combination of hot water at 60°C–80°C and aluminum sulfate may slightly improve the early strength of the Utility Fill as compared to using only hot water in the same temperature ranges.

Because the aluminum sulfate provided suitable, reliable, and repeatable results for the Rapid Set at −5°C to 10°C ambient and dry materials temperature using no mechanical heating of the mixing water (which ranged from 5°C to 10°C), the Rapid Set is deemed likely to achieve desired performance characteristics in these ranges (e.g., low risk). The Utility Fill, however, exhibits a greater degree of risk (with results reliability and repeatability) around the current best discovered approach: mechanical heating of the mixing water between 40°C and 80°C (depending on ambient and dry materials' temperature; see Table 11 for detailed recommendations).

7 Recommendations

The first recommendation involves the practical implementation of heating and maintaining the mixing water at 40°C–80°C. Table 18 summarizes the amount of heat or energy needed to use electrical heating (“heat sheets”) to heat a single 200 gal. tank from a starting temperature of 10°C to a variety of end temperatures in certain time periods.

Table 18. Recommended heat sheet sizes for heating 200 gal. plastic water tanks in a volumetric mixer.

Water Start Temp (°C)	Water End Temp (°C)	Time Required (hr)	Energy Required (MJ)	Power Required (W/sec)	Heat Sheets Total Surface Area required (in^2)
10	40	24	95	1100	880
10	40	48	95	550	440
10	60	24	158	1833	1466
10	60	48	158	916	733
10	80	24	222	2566	2053
10	80	48	222	1283	1026

The heat sheets used in all calculations in Table 18 are specifically designed for plastic containers as the heat sheets maintain a maximum temperature of 85°C. The recommendations for heat sheet total surface area assume that the outside of the tanks and heat sheets are covered in an insulating material, such as a spray foam with an approximate efficiency of insulation (R-value) of 7.* Metallic storage tanks that us a 2.5 W/in^2 heat sheet option can reduce to 12–16 hr the time to heat the water from 10°C to 60°C–80°.†

In addition to heating the mixing-water tanks externally via heat sheets, another suitable method includes immersion heaters.‡ The limiting factor for the total time required to raise the mixing water temperature to the de-

* One type of spray foam possibly suitable for this application has an R-value of 7.0 at a 1 in. spray-foam depth: http://www.spray-foam.com/compare.html.

† See the heat sheets designed for metal surfaces at: http://www.spray-foam.com/compare.html.

‡ An example immersion heating system can be found at: http://www.mcmaster.com/#immersion-heaters/=lIda1b.

sired 40°C–80°C range remains the maximum safe temperature allowed for the plastic water tank material to prevent permanent deformation or fire hazards. Any immersion heating solutions also assume that the outside of the tanks and water tank cover is covered in an insulating material with an approximate R-value of 7. Again, a spray foam may possibly be suitable for this application.

A second set of investigations should be conducted to determine the minimum confined and unconfined strength required in the variety of intended applications for the Utility Fill for horizontal surface repair when being capped with asphalt or Rapid Set. The use of hot water (60°C–80°C) allowed for a partial hydration process in the Utility Fill, resulting in a 2 hr unconfined compressive strength of 70–100 psi at −5°C (ambient and dry materials temperature). This strength has been determined in previous testing as more than adequate for repairing large blast holes in runways because the environment (blast hole) suitably confines the materials. The dominant characteristic required of the Utility Fill in this case is penetration resistance of less than 250 psi after being initially flowable when pouring the materials. The hot water testing demonstrated greater than 500 psi reliable results within 30 min of initial mixing, far exceeding this requirement. However, additional testing should be conducted to determine minimum penetration resistance and unconfined (or confined) strength required in other cases where repair requires a different surface, such as asphalt, or where repair areas may be partially or entirely unconfined.

We expect that the Utility Fill performance would significantly improve if the dry materials temperature were even slightly warmer than ambient temperature as the required set times (15–30 min) are low enough that the average materials temperature would remain significantly higher than its surroundings long enough for the early hydration process to occur. Therefore, if possible, the Utility Fill dry materials should be stored above 10°C, which would significantly improve the 30 min UCS. Future laboratory and operational testing should be conducted to quantify the increase in UCS enabled by this increase in dry materials temperature. Other options for improving the early strength gain of the Utility Fill that could also be explored involve increasing the cement content of the Utility Fill. One promising method to do this without having to add cement to the mixing bins (if this is perceived as operationally infeasible) might involve adding Type III cement to the dry mix directly in the repair hole (in layers if experimentally determined necessary to maintain consistency), adding hot water directly to the dry materials in the hole, and performing some mechanical mixing directly in the hole.

The final set of recommendations is centered on the need for operational testing of realistic size airfield repair holes (from 6 ft × 6 ft × 32 in. to large crater sizes, such as 15 ft × 15 ft × 50 in.). Operational testing is needed to validate the performance of the repair materials and repair processes in realistic environmental conditions and using actual repair equipment available to the Air Force ADR teams. One major question left unresolved is the extent of time of set and early strength gain differences for both the Utility Fill and Rapid Set materials at the same laboratory testing temperatures (ambient and ground). It is expected that the repair materials will set and gain strength faster in the operational environment because of several differences in testing, including mass of repair materials, and resulting heat transfer differences. It is expected that the laboratory test cylinders lose significantly more heat generated by the heat of hydration to the environment (air, ground) than would be expected for a typically sized repair crater. Therefore, while we expect that the laboratory tests are conservative in terms of the performance of the materials at sub-freezing temperatures, the extent of the differences is currently unknown until the conclusion of operational testing.

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Appendix A: Laboratory Test Data

Table A1. Admixture investigations, Rapid Set (task 1): mortar mix at −5°C nominal temperature, water cooled to nominal temperature before test.

Admix	Admix Combo Name	Admix 1 Amount (by % weight water)	Admix 2 Amount (by % weight water:	Penetration Resistance (psi) Time (min) 20	45	120	Workability (1–10: 1 = unworkable, 10 = pour)
Calcium Chloride	CC 15%	15%		0	0	64	5–6
Calcium Chloride, Calcium Nitrate	CC-CN 4%, 15%	4%	15%	16	40	144	5–6
	CC-CN 8%, 15%	8%	15%	0	0	96	5–6
	CC-CN 10%, 10%	10%	10%	8	40	144	5–6

Table A2. Admixture investigations, Rapid Set (task 1): mortar mix at −5°C nominal temperature, water cooled to 0°C before test.

Admix	Admix Combo Name	Admix 1 Amount (by % weight water)	Admix 2 Amount (by % weight water)	Actual Solution (g)	Mix #	Penetration Resistance (psi) Time (min) 20	45	120	Workability (1–10, 1 = unworkable, 10 = pour)
Calcium Chloride	CC 6%	6%		271	1	8	40	128	6–8
Calcium Sulfate	CS .5%	.5%		271	3	16	128	264	7–8
	CS 6%	6%		271	4	16	32	240	5–6
Calcium Chloride, Calcium Sulfate	CC-CS 6%, .5%	6%	.5%	271	5	40	40	112	5–6
	CC-CS 6%, 1%	6%	1%	271	6	8	40	80	5–6
	CC-CS 10%, 1%	10%	1%	271	7	0	24	80	5–6
Calcium Chloride, Sugar (Granular)	CC-Sug 6%, 1%	6%	1%	271	8	0	2	10	8–9
	CC-Sug 12%, 1%	12%	1%	249	9	0	32	80	6–7
	CC-Sug 6%, 2%	6%	2%	279	10	0	0	80	6–7
	CC-Sug 12%, 2%	12%	2%	271	11	0	0	40	6–7
Calcium Chloride, Calcium Nitrate	CC-CN 4%, 10%	4%	10%	249	12	8	56	176	5–6

Table A3. Admixture investigations, Rapid Set (task 1): mortar mix at −5 °C nominal temp, water cooled to 0 °C before test.

Admix	Admix Combo Name	Admix 1 Amount (by % weight water)	Admix 2 Amount (by % weight water)	Actual Solution (g)	Mix #	Penetration Resistance (psi) Time (min) 20	45	120	120	Time	psi	Time	psi
Calcium Chloride	CC 20%	20%		293	16	0	0	40		338	360		
	CC 30%	30%		293	17	0	0	8		330	120		
	CC 45%	45%		293	18	0	0	0		321	40		
Calcium Chloride, Sugar	CC-Sug 30%, 1%	30%	1%	271	19	0	0	8		313	40		
	CC-Sug 45%, 1%	45%	1%	271	20	0	0	24		305	40		
	CC-Sug 45%, 2%	45%	2%	271	21	0	0	40		297	60		
Calcium Chloride, Calcium Nitrate	CC-CN 15%, 30%	15%	30%	271	22	0	0	48		290	120		
	CC-CN 15%, 45%	15%	45%	271	23	0	16	40		282	100		
	CC-CN 30%, 30%	30%	30%	293	24	0	0	0		263	0		
	CC-CN 30%, 45%	30%	45%	316	25	0	0	40		254	60		
Calcium Chloride, Aluminum Sulfate	CC-AS 15%, 5%	15%	5%	271	26	0	0	160		271	7680		
	CC-AS 40%, 5%	40%	5%	271	27	0	8	40		244	80	273	80
Calcium Chloride, Pozzutec 20+	CC-Poz 15%, .2%	15%	.2%	271	28	0	24	152		233	400	263	52
	CC-Poz 15%, 1%	15%	1%	271	29	0	16	144		215	280	246	520
	CC-Poz 15%, 2%	15%	2%	271	30	0	16	136		206	240	240	360
Calcium Nitrate, Pozzutec 20+	CN-Poz 15%, 10%	15%	10%	271	32	0		144		222	320	259	640

Table A4. Admixture investigations, Utility Fill (task 1): −5 °C nominal temp, heat water to specified temp, mix admix into water, mix Utility Fill. Single admixtures used.

Admix	Admix Combo Name	Admix Amount (by % weight water)	Actual Solution (g)	Mix #	Penetration Resistance (psi)				Slump (in.)
					Time (min)				
					15	30	60	2 hr UCS	
Calcium Chloride	CC 5%	5%	653	50	40	208	488	0	10
	CC 15%	15%	628	51	0	0	40	0	10
Aluminum Sulfate	AS 5%	5%	767	52	40	128	432	0	10
	AS 8%	8%	810	53	80	240	640	0	10
Glenium 7500 plasticizer	Gle 1%	1%	570	55	0	144	360	0	10
	Gle 2%	2%	538	56	0	64	176	0	10
Control (no admix)			611	57	72	312	688	0	10
Calcium Chloride	CC 5%	5%	624	66	48	224	520	5	9
	CC 15%	15%	635	67	0	0	120	12	9
Aluminum Sulfate	AS 5%	5%	756	68	120	448	800	50	8
	AS 8%	8%	905	69	112	520	800	98	7
Glenium 7500 plasticizer	Gle 1% (measure in mL)	1%	499	71	64	384	760	33	9
	Gle 2% (measure in mL)	2%	524	72	16	232	560	23	10
Control (no admix)			637	73	232	520	800	74	9
Control room	(materials 20 °C)		626	74	800			507	9

Table A5. Admixture investigations, Utility Fill (task 1): −5 °C Nominal Temp, heat water to specified temp, mix admix into water, mix Utility Fill. Single and combination admixtures used.

Admix	Admix Combo Name	Admix 1 Amount (by % weight water)	Admix 2 Amount (by % weight water)	Actual Solution (g)	Mix #	Penetration Resistance (psi) Time (min) 15	60	2 hr UCS	Slump (in.)	Notes/Observations
Calcium Chloride	CC 15%	15%		375	35	0	176	0	7–8	soft/liquid at 2 hr
	CC 80%	80%		504	36	0	0	0	6–7	soft/liquid at 2 hr
Aluminum Sulfate	AS 5%	5%		357	37	0	0	0	6–7	crumbles at 2 hr
	AS 10%	10%		393	38	0	8	0	7–8	crumbles at 2 hr
	AS 15%	15%		431	39	0	0	0	6–7	crumbles at 2 hr
Sodium Sulfate	SS 5%	5%		374	40	0	0	0	8–9	soft at 2 hr
Calcium Chloride, Sodium Sulfate	CC-SS 15%, 5%	15%	5%	351	41	0	112	0	8–9	soft at 2 hr
Aluminum Sulfate, Sodium Sulfate	AS-SS 5%, 5%	5%	5%	361	43	0	24	0	7–8	soft at 2 hr
	AS-SS 8%, 8%	8%	8%	454	44	0	16	0	7–8	soft at 2 hr
Sodium Nitrate	SN 45%	45%		484	45	0	0	0	8–9	liquid at 2 hr
Aluminum Sulfate, Sodium Nitrate	AS-SN 5%, 5%	5%	5%	404	46	0	32	0	6–7	soft at 2 hr
	AS-SN 8%, 45%	8%	45%	459	47	0	0	0	7–8	soft at 2 hr
Calcium Chloride, Calcium Nitrate	CC-CN 45%, 45%	45%	45%	620	48	0	0	0	8–9	liquid at 2 hr
Aluminum Sulfate, Calcium Nitrate	AS-CN 8%, 15%	8%	15%	415	49	0	40	0	7–8	soft at 2 hr

Table A6. Utility Fill and Rapid Set hot water test phase (task 2).

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr1.1	464			10	20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.1					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.1					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.1					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.2	760			10	20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.2					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.2					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.2					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.3	760			10	20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.3					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.3					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.3					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.1					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.2					20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.1	500		8		20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.2	500		7		20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr1.3	500		7		20	20	UF	3.75	1:0.89:13.3:0	9.5
penetr2.1	120			8	20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.1	288			10	20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.1					20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.1					20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.2	152			8	20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.2	424			10	20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.2					20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.2					20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.3	240			8	20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.3	528			10	20	20	UF	4	1:0.95:13.3:0	9.75

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr2.3					20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.3					20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.1					20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.2					20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.1	500		10		20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.2	500		9		20	20	UF	4	1:0.95:13.3:0	9.75
penetr2.3	500		9		20	20	UF	4	1:0.95:13.3:0	9.75
penetr4.1	232			5	20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.1	800			7	20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.1					20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.1					20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.2	192			5	20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.2	800			7	20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.2					20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.2					20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.3	312			5	20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.3	800			7	20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.3					20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.3					20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.1					20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.2					20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.1	500		6		20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.2	500		6		20	60	UF	4.5	1:1.07:13.3:0	9
penetr4.3	500		6		20	60	UF	4.5	1:1.07:13.3:0	9
penetr5.1	48			10	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.1	480			15	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.1	1160			20	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.1	5200			30	20	5	UF	3.75	1:0.89:13.3:0	11

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr5.2	48			10	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.2	440			15	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.2	1280			20	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.2	6000			30	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.3	56			10	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.3	376			15	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.3	1520			20	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.3	4800			30	20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.1					20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.2					20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.1	500		12.5		20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.2	500		12.5		20	5	UF	3.75	1:0.89:13.3:0	11
penetr5.3	500		12.5		20	5	UF	3.75	1:0.89:13.3:0	11
penetr7.1	112			7	10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.1	496			9	10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.1					10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.1					10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.2	152			7	10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.2	544			9	10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.2					10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.2					10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.3	200			7	10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.3	760			9	10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.3					10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.3					10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.1					10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.2					10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.1	500		8		10	60	UF	4.25	1:1.01:13.3:0	6.25

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr7.2	500		8		10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr7.3	500		8		10	60	UF	4.25	1:1.01:13.3:0	6.25
penetr8.1	0			10	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.1	8			15	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.1	64			20	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.1	300			25	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.2	0			10	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.2	8			15	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.2	72			20	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.2	296			25	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.3	0			10	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.3	24			15	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.3	88			20	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.3	328			25	10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.1					10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.2					10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.1	500		22.5		10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.2	500		22.5		10	20	UF	4.25	1:1.01:13.3:0	11
penetr8.3	500		22.5		10	20	UF	4.25	1:1.01:13.3:0	11
penetr9.1	0			10	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.1	0			15	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.1	64			20	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.1	112			25	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.2	0			10	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.2	0			15	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.2	40			20	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.2	136			25	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.3	0			10	10	5	UF	4.25	1:1.01:13.3:0	11

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr9.3	0			15	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.3	48			20	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.3	136			25	10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.1					10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.2					10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.1	500		27.5		10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.2	500		27.5		10	5	UF	4.25	1:1.01:13.3:0	11
penetr9.3	500		27.5		10	5	UF	4.25	1:1.01:13.3:0	11
penetr10.1	0			15	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.1	0			25	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.1	40			30	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.1	96			35	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.2	0			15	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.2	0			25	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.2	44			30	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.2	88			35	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.3	0			15	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.3	0			25	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.3	40			30	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.3	80			35	0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.1					0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.2					0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.1					0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.2					0	20	UF	4	1:0.95:13.3:0	10.75
penetr10.3					0	20	UF	4	1:0.95:13.3:0	10.75
penetr11.1	304			12	0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.1	544			14	0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.1	800				0	60	UF	4	1:0.95:13.3:0	7.25

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr11.1					0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.2	110			12	0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.2	496			14	0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.2	800				0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.2					0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.3	376			12	0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.3	632			14	0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.3	800				0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.3					0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.1					0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.2					0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.1	500		9		0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.2	500		11		0	60	UF	4	1:0.95:13.3:0	7.25
penetr11.3	500		9		0	60	UF	4	1:0.95:13.3:0	7.25
penetr13.1	40			10	-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.1	288				-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.1					-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.1					-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.2	200			10	-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.2	576				-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.2					-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.2					-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.3	152			10	-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.3	576				-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.3					-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.3					-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.1					-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.2					-15	90	UF	4.25	1:1.01:13.3:0	1

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr13.1					-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.2					-15	90	UF	4.25	1:1.01:13.3:0	1
penetr13.3					-15	90	UF	4.25	1:1.01:13.3:0	1
penetr15.1	0			15	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.1	40			20	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.1	96			30	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.1	224			45	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.2	0			15	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.2	16			20	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.2	80			30	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.2	200			45	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.3	0			15	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.3	16			20	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.3	72			30	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.3	184			45	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.1		8		120	-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.2					-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.1		8			-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.2					-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr15.3					-15	61.8	UF	4	1:0.95:13.3:0	10.75
penetr16.1	0			10	-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.1	80			15	-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.1	680				-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.1					-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.2	8			10	-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.2	168			15	-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.2	800				-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.2					-5	61	UF	4.25	1:1.01:13.3:0	9.25

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr16.3	0			10	-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.3	120			15	-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.3	696				-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.3					-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.1					-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.2					-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.1	500		14		-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.2	500		14		-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr16.3	500		14		-5	61	UF	4.25	1:1.01:13.3:0	9.25
penetr17.1	0			15	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.1	16			20	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.1	72			30	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.1	240			35	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.2	0			15	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.2	24			20	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.2	72			30	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.2	224			35	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.3	0			15	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.3	24			20	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.3	80			30	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.3	272			35	-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.1					-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.2					-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.1					-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.2					-5	40	UF	4	1:0.95:13.3:0	10.5
penetr17.3					-5	40	UF	4	1:0.95:13.3:0	10.5
penetr18.1	40			12	-5	60	UF	4	1:0.95:13.3:0	9
penetr18.1	160			15	-5	60	UF	4	1:0.95:13.3:0	9

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr18.1	472			17	-5	60	UF	4	1:0.95:13.3:0	9
penetr18.1					-5	60	UF	4	1:0.95:13.3:0	9
penetr18.2	16			12	-5	60	UF	4	1:0.95:13.3:0	9
penetr18.2	64			15	-5	60	UF	4	1:0.95:13.3:0	9
penetr18.2	144			17	-5	60	UF	4	1:0.95:13.3:0	9
penetr18.2	300				-5	60	UF	4	1:0.95:13.3:0	9
penetr18.3					-5	60	UF	4	1:0.95:13.3:0	9
penetr18.3					-5	60	UF	4	1:0.95:13.3:0	9
penetr18.3					-5	60	UF	4	1:0.95:13.3:0	9
penetr18.3					-5	60	UF	4	1:0.95:13.3:0	9
penetr18.1		195		120	-5	60	UF	4	1:0.95:13.3:0	9
penetr18.2		154		120	-5	60	UF	4	1:0.95:13.3:0	9
penetr18.1	500	195	15		-5	60	UF	4	1:0.95:13.3:0	9
penetr18.2	500	154	16		-5	60	UF	4	1:0.95:13.3:0	9
penetr18.3					-5	60	UF	4	1:0.95:13.3:0	9
penetr19.1	0			20	-5	40	UF	4	1:0.95:13.3:0	10
penetr19.1	176			35	-5	40	UF	4	1:0.95:13.3:0	10
penetr19.1	300			50	-5	40	UF	4	1:0.95:13.3:0	10
penetr19.1	800				-5	40	UF	4	1:0.95:13.3:0	10
penetr19.2	0			20	-5	40	UF	4	1:0.95:13.3:0	10
penetr19.2	40			35	-5	40	UF	4	1:0.95:13.3:0	10
penetr19.2	192			50	-5	40	UF	4	1:0.95:13.3:0	10
penetr19.2	440				-5	40	UF	4	1:0.95:13.3:0	10
penetr19.3					-5	40	UF	4	1:0.95:13.3:0	10
penetr19.3					-5	40	UF	4	1:0.95:13.3:0	10
penetr19.3					-5	40	UF	4	1:0.95:13.3:0	10
penetr19.3					-5	40	UF	4	1:0.95:13.3:0	10
penetr19.1		11		120	-5	40	UF	4	1:0.95:13.3:0	10

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr19.2		6		120	-5	40	UF	4	1:0.95:13.3:0	10
penetr19.1		11			-5	40	UF	4	1:0.95:13.3:0	10
penetr19.2		6			-5	40	UF	4	1:0.95:13.3:0	10
penetr19.3					-5	40	UF	4	1:0.95:13.3:0	10
penetr20.1	320			15	20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.1	2200				20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.1					20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.1					20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.2	328			15	20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.2	1840				20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.2					20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.2					20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.3					20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.3					20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.3					20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.3					20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.1		857		120	20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.2		830		120	20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.1	500	857	9		20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.2	500	830	9		20	20	UF	4	1:0.95:13.3:0	9.75
penetr20.3					20	20	UF	4	1:0.95:13.3:0	9.75
penetr21.1	40			10	20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.1	200			15	20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.1	1600			20	20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.1					20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.2	56			10	20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.2	288			15	20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.2	1520			20	20	5.1	UF	4	1:0.95:13.3:0	10

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr21.2					20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.3					20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.3					20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.3					20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.3					20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.1		1245		120	20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.2		822		120	20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.1	500	1245	17.5		20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.2	500	822	15		20	5.1	UF	4	1:0.95:13.3:0	10
penetr21.3					20	5.1	UF	4	1:0.95:13.3:0	10
penetr22.1	0			15	20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.1	0			20	20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.1	16			25	20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.1	24			30	20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.2	0			15	20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.2	0			20	20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.2	16			25	20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.2				30	20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.3					20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.3					20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.3					20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.3					20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.1		4896		120	20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.2		4784		120	20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.1	500	4896	35		20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.2	500	4784	35		20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr22.3					20	20	RapSet	7.1	1:0.37:13.3:0	9
penetr23.1	0			30	0	60	RapSet	7.1	1:0.37:13.3:0	9

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr23.1	0			45	0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.1	0			55	0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.1					0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.2	0			30	0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.2	0			45	0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.2	0			55	0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.2					0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.3					0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.3					0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.3					0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.3					0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.1		3780		120	0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.2		3758		120	0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.1	500	3780	80		0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.2	500	3758	80		0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr23.3	500		80		0	60	RapSet	7.1	1:0.37:13.3:0	9
penetr24.1	0			15	0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.1	0			20	0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.1	800			30	0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.1				35	0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.2	0			15	0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.2	0			20	0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.2	24			30	0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.2	56			35	0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.3					0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.3					0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.3					0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.3					0	90	RapSet	7.1	1:0.37:13.3:0	8.5

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr24.1		4428		120	0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.2		4417		120	0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.1	500	4428	25		0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.2	500	4417	60		0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr24.3					0	90	RapSet	7.1	1:0.37:13.3:0	8.5
penetr25.1	0			15	10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.1	0			25	10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.1	16			35	10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.1	32			45	10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.2	0			15	10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.2	0			25	10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.2	0			35	10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.2	24			45	10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.3					10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.3					10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.3					10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.3					10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.1		3860		120	10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.2		3871		120	10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.1	500	3860	70		10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.2	500	3871	70		10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr25.3					10	20	RapSet	8	1:0.41:13.3:0	8.5
penetr26.1	16			15	10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.1	120			20	10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.1	800			25	10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.1				35	10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.2	72			15	10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.2	800			20	10	60	RapSet	6.8	1:0.35:13.3:0	5

Sample	PenRes_(psi)	2hr_UCS_(psi)	SetTime_(min)	Time_elaps_(min)	Nom_Temp_C	Water Temp	Mixture	water_lb	ratio_mix	Slump
penetr26.2				25	10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.2				35	10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.3					10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.3					10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.3					10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.3					10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.1		4899		120	10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.2		4334		120	10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.1	500	4899	30		10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.2	500	4334	30		10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr26.3					10	60	RapSet	6.8	1:0.35:13.3:0	5
penetr27.1				15	-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.1				20	-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.1				30	-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.1				40	-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.2				15	-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.2				20	-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.2				30	-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.2				40	-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.3					-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.3					-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.3					-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.3					-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.1		>3500		120	-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.2					-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.1	500	>3500	42.5		-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.2	500		35		-5	90	RapSet	6.6	1:0.34:13.3:0	4.75
penetr27.3					-5	90	RapSet	6.6	1:0.34:13.3:0	4.75

Table A7. Aluminum Sulfate Rapid Set Test Phase (task 3). All tests listed are using 60 lb dry Rapid Set mix. Admixture type (if used) is Aluminum Sulfate.

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr1.1	8			15	0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.1	48			25	0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.1	800			35	0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.1	0			0	0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.2	0			15	0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.2	52			25	0	0.0%	20	7.1	1:0.37:1:1.1	4	0	1
penetr1.2	800			35	0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.2					0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.3					0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.3					0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.3					0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.3					0	0.0%	20	7.1	1:0.37:1:1.1	4	0	1
penetr1.1		4858		115	0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.2		4958		120	0	0.0%	20	7.1	1:0.37:1:1.1	4	0	1
penetr1.3		4970		125	0	0.0%	20	7.1	1:0.37:1:1.1	4	0	1
penetr1.1	500	4858	30		0	0.0%	20	7.1	1:0.37:1:1.1	4	0	1
penetr1.2	500	4970	30		0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr1.3					0	0.0%	20	7.1	1:0.37:1:1.1	4	1	0
penetr2.1	0			15	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.1	24			20	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.1	264			30	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.1	8000			35	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.2	0			15	0	0.0%	20	8.1	1:0.42:1:1.1	6	0	1
penetr2.2	28			20	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.2	800			30	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.2	8000			35	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr2.3	0			15	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.3	32			20	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.3	504			30	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.3	8000			35	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.1		5399		120	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.2		5292		120	0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.3					0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.1	500	5399	32.5		0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.2	500	5292	25		0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr2.3	500		30		0	0.0%	20	8.1	1:0.42:1:1.1	6	1	0
penetr3.1	0			15	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.1	0			20	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	0	1
penetr3.1	40			35	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.1	800			40	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.2	0			15	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.2	0			20	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	0	1
penetr3.2	40			35	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.2	800			40	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.3	0			15	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.3	0			20	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.3	40			35	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	0	1
penetr3.3	800			40	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.1		4529		120	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	0	1
penetr3.2		4685		120	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.3		4562		125	0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr3.1	500	4529	37.5		0	0.0%	20	8.1	1:0.44:1.1:1.2	9	0	1
penetr3.2	500	4685	37.5		0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr3.3	500	4562	37.5		0	0.0%	20	8.1	1:0.44:1.1:1.2	9	1	0
penetr4.1	8			15	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.1	40			20	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.1	104			25	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.1	800			30	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.2	8			15	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.2	40			20	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	0	1
penetr4.2	108			25	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.2	800			30	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.3	0			0	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	0	1
penetr4.3	0			0	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	0	1
penetr4.3	0			0	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.3	0			0	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.1		5192		120	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.2		5572		120	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.3		5181		125	0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.1	500	5181	27.5		0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.2	500	5572	27.5		0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.3					0	0.0%	20	8.1	1:0.4:0.9:1	6.5	1	0
penetr4.1.1	0			15	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	0	1
penetr4.1.1	5840			20	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0
penetr4.1.1	0			0	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0
penetr4.1.1	0			0	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	0	1
penetr4.1.2	0			15	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	0	1
penetr4.1.2	4160			20	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0
penetr4.1.2	0			0	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0
penetr4.1.2	0			0	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr4.1.3	0			0	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	0	1
penetr4.1.3	0			0	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	0	1
penetr4.1.3	0			0	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0
penetr4.1.3	0			0	100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0
penetr4.1.1		3757			100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0
penetr4.1.2		3645			100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0
penetr4.1.3		3489			100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0
penetr4.1.1	500	3757	17.5		100	0.0%	20	8.1	1:0.42:1:1.1	6.5	0	1
penetr4.1.2	500	3489	17.5		100	0.0%	20	8.1	1:0.42:1:1.1	6.5	0	1
penetr4.1.3					100	0.0%	20	8.1	1:0.42:1:1.1	6.5	1	0
penetr5.1	0			25	101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.1	0			35	101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.1	16			40	101	1.2%	5	8.1	1:0.42:1:1.1	8	0	1
penetr5.1	800			63	101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.2	0			25	101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.2	0			35	101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.2	20			40	101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.2	800			63	101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.3	0			25	101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.3	0			35	101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.3	24			55	101	1.2%	5	8.1	1:0.42:1:1.1	8	0	1
penetr5.3	800			63	101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.1		3452			101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.2		3160			101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.3					101	1.2%	5	8.1	1:0.42:1:1.1	8	0	1
penetr5.1	500	3452	51.5		101	1.2%	5	8.1	1:0.42:1:1.1	8	0	1
penetr5.2	500	3160	51.5		101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr5.3	500		59		101	1.2%	5	8.1	1:0.42:1:1.1	8	1	0
penetr5.1.1	0			15	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.1	16			25	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.1	152			30	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	0	1
penetr5.1.1	8000			32	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	0	1
penetr5.1.2	0			15	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.2	16			25	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.2	144			30	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	0	1
penetr5.1.2	80			32	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.3	0			15	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.3	40			25	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.3	800			30	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.3	0			0	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	0	1
penetr5.1.1		3441		120	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.2		3497		120	202	2.3%	5	7.1	1:0.37:1:1.1	4.75	0	1
penetr5.1.3					202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.1	500	3441	31		202	2.3%	5	7.1	1:0.37:1:1.1	4.75	0	1
penetr5.1.2					202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.1.3	500	3497	27.5		202	2.3%	5	7.1	1:0.37:1:1.1	4.75	1	0
penetr5.2.1	0			15	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.1	800			20	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.1	5600			21	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.1	0			0	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.2	0			15	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.2	800			20	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.2	7200			21	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.2	0			0	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	0	1

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr5.2.3	0			15	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.3	800			20	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.3	6400			21	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.3	0			0	300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.1		2883			300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.2		2749			300	3.4%	5	9.1	1:0.47:1:1.1	3.5	0	1
penetr5.2.3					300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.1	500	2883	17.5		300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.2		2749	17.5		300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr5.2.3	500		17.5		300	3.4%	5	9.1	1:0.47:1:1.1	3.5	1	0
penetr6.1	0			45	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.1	0			55	160	1.8%	5	9.1	1:0.47:1:1.1	5	0	1
penetr6.1	16			60	160	1.8%	5	9.1	1:0.47:1:1.1	5	0	1
penetr6.1	624			70	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.2	0			45	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.2	0			55	160	1.8%	5	9.1	1:0.47:1:1.1	5	0	1
penetr6.2	16			60	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.2	40			70	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.3	0			45	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.3	16			55	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.3	24			60	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.3	160			70	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.1		4183		120	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.2		3952		120	160	1.8%	5	9.1	1:0.47:1:1.1	5	0	1
penetr6.3		3627		125	160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.1	500	4183	65		160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr6.2	500	3952	71.5		160	1.8%	5	9.1	1:0.47:1:1.1	5	0	1

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr6.3	500	3627	71.5		160	1.8%	5	9.1	1:0.47:1:1.1	5	1	0
penetr8.1	0			15	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.1	16			30	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.1	800			40	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.1	0			0	300	3.4%	-5	9.1	1:0.47:1:1.1	4	0	1
penetr8.2	0			15	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.2	28			30	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.2	800			40	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.2	0			0	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.3	0			15	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.3	32			30	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.3	800			40	300	3.4%	-5	9.1	1:0.47:1:1.1	4	0	1
penetr8.3	0			0	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.1		3052		120	300	3.4%	-5	9.1	1:0.47:1:1.1	4	0	1
penetr8.2		3162		120	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.3				125	300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.1	500	3052	35		300	3.4%	-5	9.1	1:0.47:1:1.1	4	1	0
penetr8.2	500	3162	35		300	3.4%	-5	9.1	1:0.47:1:1.1	4	0	1
penetr8.3	500		35		300	3.4%	-5	9.1	1:0.47:1:1.1	4	0	1
penetr9.1	0			15	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.1	8			25	350	4.0%	-5	9.6	1:0.5:1:1.1	5	0	1
penetr9.1	28			35	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.1	592			40	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.2	0			15	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.2	8			25	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.2	28			35	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.2	508			40	350	4.0%	-5	9.6	1:0.5:1:1.1	5	0	1

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr9.3	0			15	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.3	8			25	350	4.0%	-5	9.6	1:0.5:1:1.1	5	0	1
penetr9.3	32			35	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.3	544			40	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.1		3757		120	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.2		3645		120	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.3				125	350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.1	500	3757	37.5		350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.2	500	3645	40		350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr9.3					350	4.0%	-5	9.6	1:0.5:1:1.1	5	1	0
penetr10.1	40			10	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.1	248			13	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.1	800			15	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.1	0			0	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.2	81			10	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.2	800			13	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.2	0			0	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.2	0			0	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.3	0			0	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.3	0			0	500	5.7%	-5	10.1	1:0.52:1:1.1	1	0	1
penetr10.3	0			0	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.3	0			0	500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.1		3286			500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.2		3371			500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.3					500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.1	500	3286	14		500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr10.2	500	3371	11.5		500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr10.3	500				500	5.7%	-5	10.1	1:0.52:1:1.1	1	1	0
penetr11.1	0			15	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.1	16			20	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.1	200			35	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.1	8000			45	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.2	0			15	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.2	16			20	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	0	1
penetr11.2	280			35	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	0	1
penetr11.2	8000			45	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	0	1
penetr11.3	0			0	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.3	0			0	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.3	0			0	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.3	0			0	450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.1					450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.2					450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.3					450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	0	1
penetr11.1	500		40		450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.2	500		40		450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr11.3	500				450	5.1%	-10	8.6	1:0.44:1:1.1	1.5	1	0
penetr12.1	0			15	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.1	0			30	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.1	0			45	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.1	800			59	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.2	0			15	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.2	0			30	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.2	0			45	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	0	1
penetr12.2	680			59	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr12.3	0			15	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	0	1
penetr12.3	0			30	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	0	1
penetr12.3	0			45	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	0	1
penetr12.3	800			59	300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.1		34			300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	0	1
penetr12.2		688			300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.3					300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.1	500	34	52		300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.2	500	688	52		300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr12.3	500		52		300	3.4%	-10	9.1	1:0.47:1:1.1	9.5	1	0
penetr13.1	0			15	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.1	0			30	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.1	64			45	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.1	760			55	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.2	0			15	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.2	0			30	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.2	32			45	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.2	640			55	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.3	0			15	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.3	0			30	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.3	16			45	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.3	608			55	300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.1		1159			300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.2		1582			300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.3					300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	0	1
penetr13.1	500	1159	50		300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0
penetr13.2	500	1582	50		300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr13.3	500		50		300	3.4%	-10	8.6	1:0.44:1:1.1	9.25	0	1
penetr13.2.1	88			15	300	3.4%	-10	7.6	1:0.39:1:1.1	9.25	1	0
penetr13.2.1	800			40	300	3.4%	-10	7.6	1:0.39:1:1.1	9.25	0	1
penetr13.2.1	0			45	300	3.4%	-10	7.6	1:0.39:1:1.1	9.25	1	0
penetr13.2.1	0			0	300	3.4%	-10	7.6	1:0.39:1:1.1	9.25	1	0
penetr13.2.2	168			15	300	3.4%	-10	7.6	1:0.39:1:1.1	4	1	0
penetr13.2.2	800			40	300	3.4%	-10	7.6	1:0.39:1:1.1	4	0	1
penetr13.2.2	0			45	300	3.4%	-10	7.6	1:0.39:1:1.1	4	1	0
penetr13.2.2	0			0	300	3.4%	-10	7.6	1:0.39:1:1.1	4	1	0
penetr13.2.3	768			0	300	3.4%	-10	7.6	1:0.39:1:1.1	4	1	0
penetr13.2.3	0			0	300	3.4%	-10	7.6	1:0.39:1:1.1	4	0	1
penetr13.2.3	0			0	300	3.4%	-10	7.6	1:0.39:1:1.1	4	0	1
penetr13.2.3	0			0	300	3.4%	-10	7.6	1:0.39:1:1.1	4	0	1
penetr13.2.1		2236			300	3.4%	-10	7.6	1:0.39:1:1.1	4	1	0
penetr13.2.2		2474			300	3.4%	-10	7.6	1:0.39:1:1.1	4	1	0
penetr13.2.3					300	3.4%	-10	7.6	1:0.39:1:1.1	4	1	0
penetr13.2.1	500	2236	42.5		300	3.4%	-10	7.6	1:0.39:1:1.1	4	0	1
penetr13.2.2	500	2474	42.5		300	3.4%	-10	7.6	1:0.39:1:1.1	4	1	0
penetr13.2.3	500				300	3.4%	-10	7.6	1:0.39:1:1.1	4	0	1
penetr14.1	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.1	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	0	1
penetr14.1	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.1	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.2	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.2	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	0	1
penetr14.2	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	0	1
penetr14.2	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	0	1

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr14.3	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.3	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.3	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	0	1
penetr14.3	0			0	300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.1					300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.2					300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.3					300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.1	500		7		300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.2	500		7		300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.3	500		7		300	3.4%	10	8.6	1:0.44:1:1.1	0	1	0
penetr14.1.1	16			15	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.1	88			17	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.1	800			18	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.1	0			0	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.2	8			15	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	0	1
penetr14.1.2	168			17	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	0	1
penetr14.1.2	800			18	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.2	0			0	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.3	16			15	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.3	768			17	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.3	0			0	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.3	0			0	300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.1		3017			300	3.4%	10	10.6	1:0.55:1:1.1	3.5	0	1
penetr14.1.2		3155			300	3.4%	10	10.6	1:0.55:1:1.1	3.5	0	1
penetr14.1.3		3140			300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.1	500	3017	17.5		300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr14.1.2	500	3155	17.5		300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr14.1.3	500	3140	16		300	3.4%	10	10.6	1:0.55:1:1.1	3.5	1	0
penetr15.1	0			40	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	0	1
penetr15.1	8			45	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	0	1
penetr15.1	104			50	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.1	800			52	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.2	0			30	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.2	0			40	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.2	216			45	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.2	800			50	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.3	0			30	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	0	1
penetr15.3	0			40	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.3	96			45	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.3	800			50	100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.1		3157			100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.2		2961			100	1.1%	10	8.1	1:0.42:1:1.1	9.75	0	1
penetr15.3					100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.1	500	3157	51		100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr15.2	500	2961	47.5		100	1.1%	10	8.1	1:0.42:1:1.1	9.75	0	1
penetr15.3	500		47.5		100	1.1%	10	8.1	1:0.42:1:1.1	9.75	1	0
penetr16.1	16			15	200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.1	240			19	200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.1	800			21	200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.1	0			0	200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.2	0			15	200	2.3%	10	8.6	1:0.44:1:1.1	3	0	1
penetr16.2	336			19	200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.2	800			21	200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.2	0			0	200	2.3%	10	8.6	1:0.44:1:1.1	3	0	1

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr16.3	32			15	200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.3	800			19	200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.3	0			0	200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.3	0			0	200	2.3%	10	8.6	1:0.44:1:1.1	3	0	1
penetr16.1		2906			200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.2		2955			200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.3					200	2.3%	10	8.6	1:0.44:1:1.1	3	0	1
penetr16.1	500	2906	20		200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.2	500	2955	20		200	2.3%	10	8.6	1:0.44:1:1.1	3	1	0
penetr16.3	500		17		200	2.3%	10	8.6	1:0.44:1:1.1	3	0	1
penetr17.1	0			20	300	3.4%	0	7.1	1:0.37:1:1.1	0	0	1
penetr17.1	24			30	300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.1	8000			35	300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.1	0			0	300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.2	0			20	300	3.4%	0	7.1	1:0.37:1:1.1	0	0	1
penetr17.2	24			30	300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.2	7200			35	300	3.4%	0	7.1	1:0.37:1:1.1	0	0	1
penetr17.2	0			0	300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.3	0			0	300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.3	0			0	300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.3	0			0	300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.3	0			0	300	3.4%	0	7.1	1:0.37:1:1.1	0	0	1
penetr17.1		2624			300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.2		2912			300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.3					300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.1	500	2624	32.5		300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr17.2	500	2912	32.5		300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr17.3	500				300	3.4%	0	7.1	1:0.37:1:1.1	0	1	0
penetr18.1	0			15	200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.1	16			30	200	2.3%	0	7.6	1:0.39:1:1.1	5	0	1
penetr18.1	480			40	200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.1	0			0	200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.2	0			15	200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.2	16			30	200	2.3%	0	7.6	1:0.39:1:1.1	5	0	1
penetr18.2	720			40	200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.2	0			0	200	2.3%	0	7.6	1:0.39:1:1.1	5	0	1
penetr18.3	0			0	200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.3	0			0	200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.3	0			0	200	2.3%	0	7.6	1:0.39:1:1.1	5	0	1
penetr18.3	0			0	200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.1		3230			200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.2		3226			200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.3					200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.1	500	3230	41		200	2.3%	0	7.6	1:0.39:1:1.1	5	0	1
penetr18.2	500	3226	35		200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr18.3	500				200	2.3%	0	7.6	1:0.39:1:1.1	5	1	0
penetr19.1	0			15	200	2.3%	-5	8.1	1:0.42:1:1.1	7	0	1
penetr19.1	0			25	200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.1	0			35	200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.1	16			60	200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.2	0			0	200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.2	0			0	200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.2	0			0	200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.2	64			0	200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr19.3	0			0	200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.3	0			0	200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.3	0			0	200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.3	0			0	200	2.3%	-5	8.1	1:0.42:1:1.1	7	0	1
penetr19.1		2426			200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.2		2132			200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.3					200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.1	500	2426			200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.2	500	2132			200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr19.3	500				200	2.3%	-5	8.1	1:0.42:1:1.1	7	1	0
penetr20.1	8			15	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.1	800			25	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.1	0			0	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.1	0			0	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.2	0			15	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.2	320			25	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.2	640			29	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.2	0			0	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.3	16			15	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.3	640			25	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.3	800			29	750	8.5%	-15	9.1	1:0.47:1:1.1	8	0	1
penetr20.3	0			0	750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.1		822			750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.2		889			750	8.5%	-15	9.1	1:0.47:1:1.1	8	0	1
penetr20.3					750	8.5%	-15	9.1	1:0.47:1:1.1	8	0	1
penetr20.1	500	822	20		750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0
penetr20.2	500	889	27		750	8.5%	-15	9.1	1:0.47:1:1.1	8	1	0

Sample	PenRes_ (psi)	2hr_UCS_ (psi)	SetTime_ (min)	Time_elaps_ (min)	Admix_ wt_g	Admix_% (wt.cem)	Nom_Temp_ C	water_ lb	ratio_mix	Slump	Train	Test
penetr20.3	500		20		750	8.5%	-15	9.1	1:0.47:1:1.1	8	0	1
penetr21.1	0			10	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	0	1
penetr21.1	144			15	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	1	0
penetr21.1	800			20	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	0	1
penetr21.1	0			0	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	1	0
penetr21.2	16			10	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	1	0
penetr21.2	136			15	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	0	1
penetr21.2	800			20	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	1	0
penetr21.2	0			0	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	0	1
penetr21.3	0			0	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	0	1
penetr21.3	0			0	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	0	1
penetr21.3	0			0	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	0	1
penetr21.3	0			0	400	4.6%	0	8.6	1:0.44:1:1.1	6.5	1	0
penetr21.1		2204			400	4.6%	0	8.6	1:0.44:1:1.1	6.5	0	1
penetr21.2		2252			400	4.6%	0	8.6	1:0.44:1:1.1	6.5	0	1
penetr21.3					400	4.6%	0	8.6	1:0.44:1:1.1	6.5	0	1
penetr21.1	500	2204	17.5		400	4.6%	0	8.6	1:0.44:1:1.1	6.5	1	0
penetr21.2	500	2252	17.5		400	4.6%	0	8.6	1:0.44:1:1.1	6.5	1	0
penetr21.3	500				400	4.6%	0	8.6	1:0.44:1:1.1	6.5	1	0

Appendix B: Additional Figures and Tables

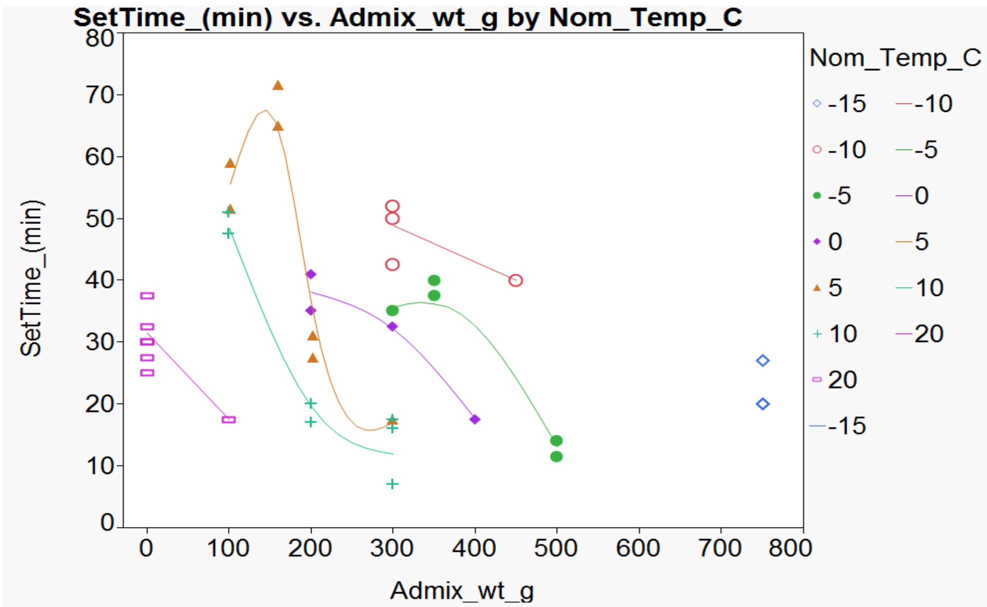


Figure B1. Task 3 (aluminum sulfate) testing: set time (time to reach 500 psi, in min) vs. the amount of aluminum sulfate used (g), filtered by testing temperature (°C). All completed tests in task 3 are shown.

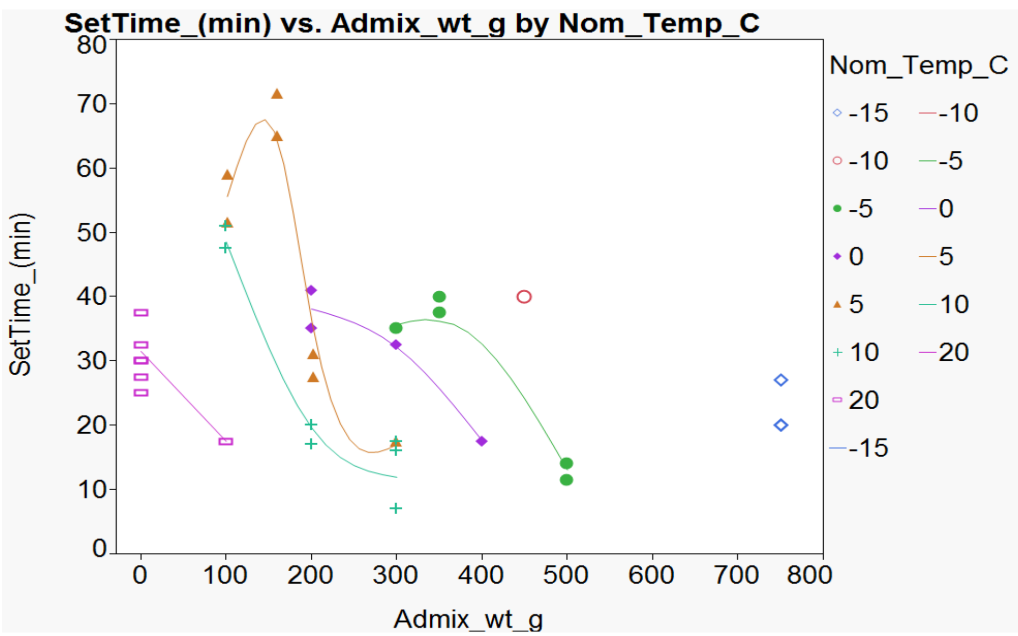


Figure B2. Task 3 (aluminum sulfate) testing: set time (time to reach 500 psi, in min) vs. the amount of aluminum sulfate used (g), filtered by testing temperature (°C). Tests shown only where 2 hr UCS is greater than 2500 psi.

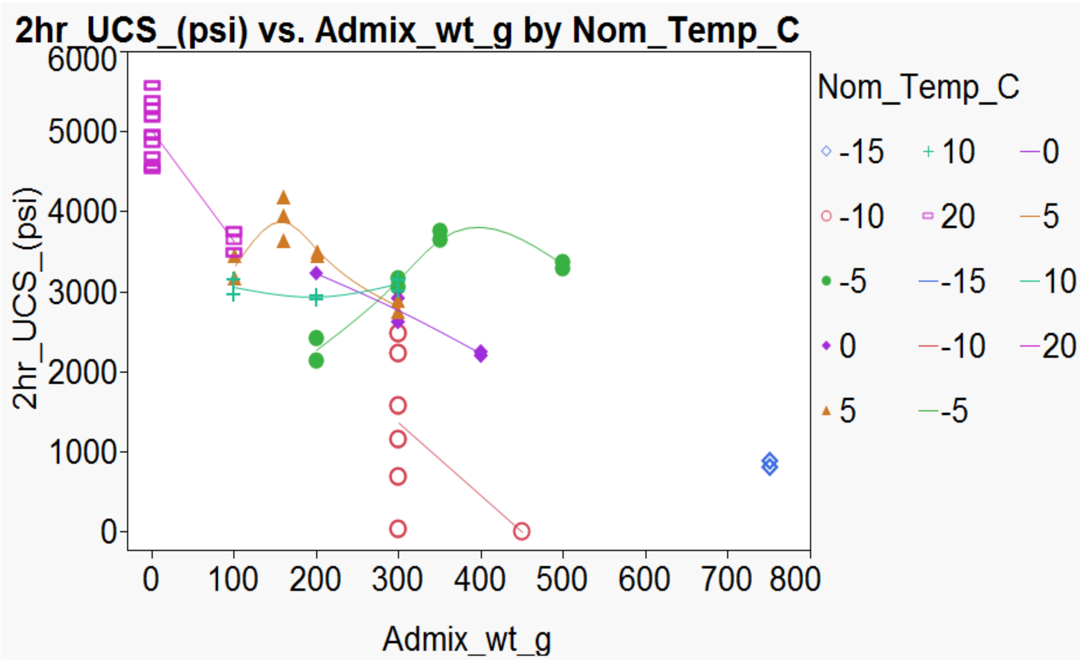


Figure B3. Task 3 (aluminum sulfate) testing: 2 hr UCS vs. the amount of aluminum sulfate used (g), filtered by testing temperature (°C). All completed tests in task 3 are shown.

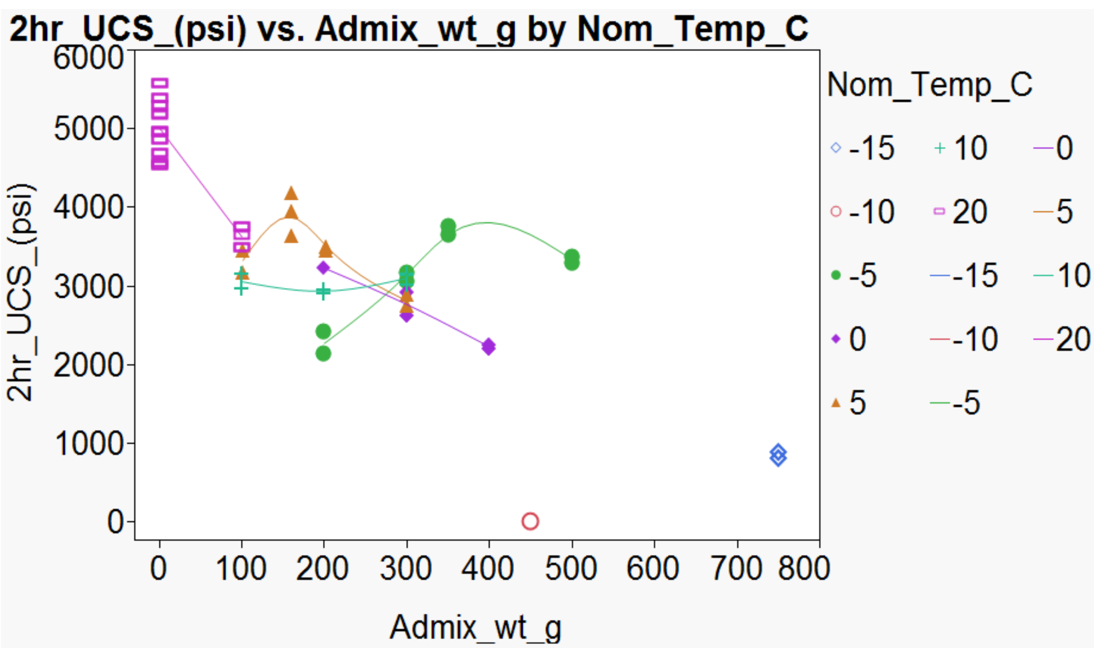


Figure B4. Task 3 (aluminum sulfate) testing: 2 hr UCS vs. amount of aluminum sulfate used (g), filtered by testing temperature (°C). Tests shown only where 2 hr UCS is greater than 2500 psi.

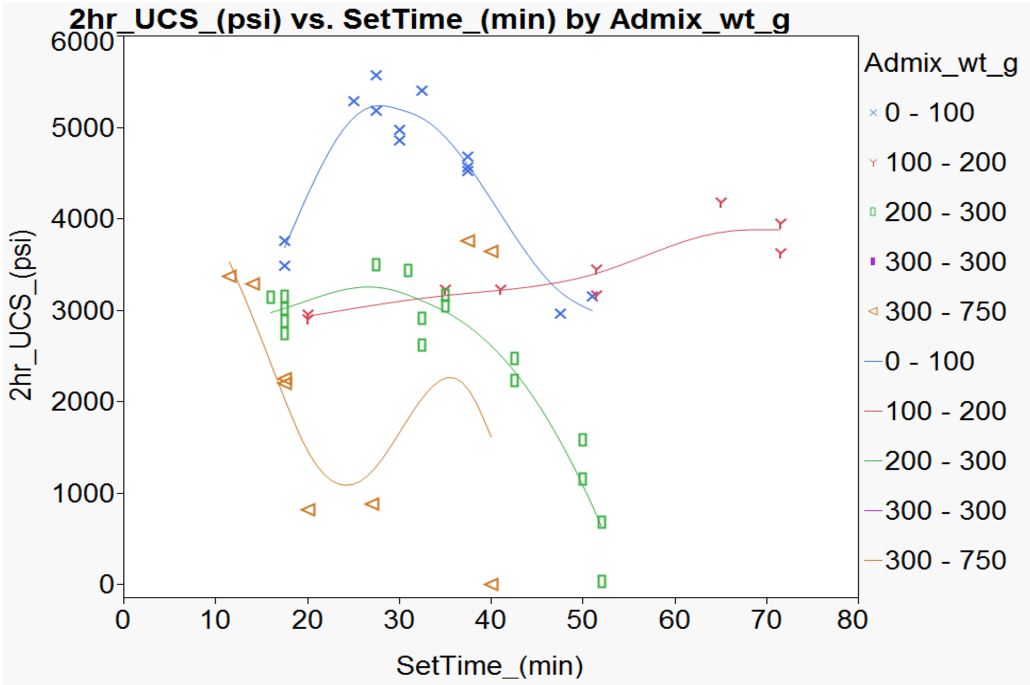


Figure B5. Task 3 (aluminum sulfate) testing: 2 hr UCS vs. set time (time to reach 500 psi, in min), filtered by the amount of aluminum sulfate used (g). All completed tests in task 3 are shown.

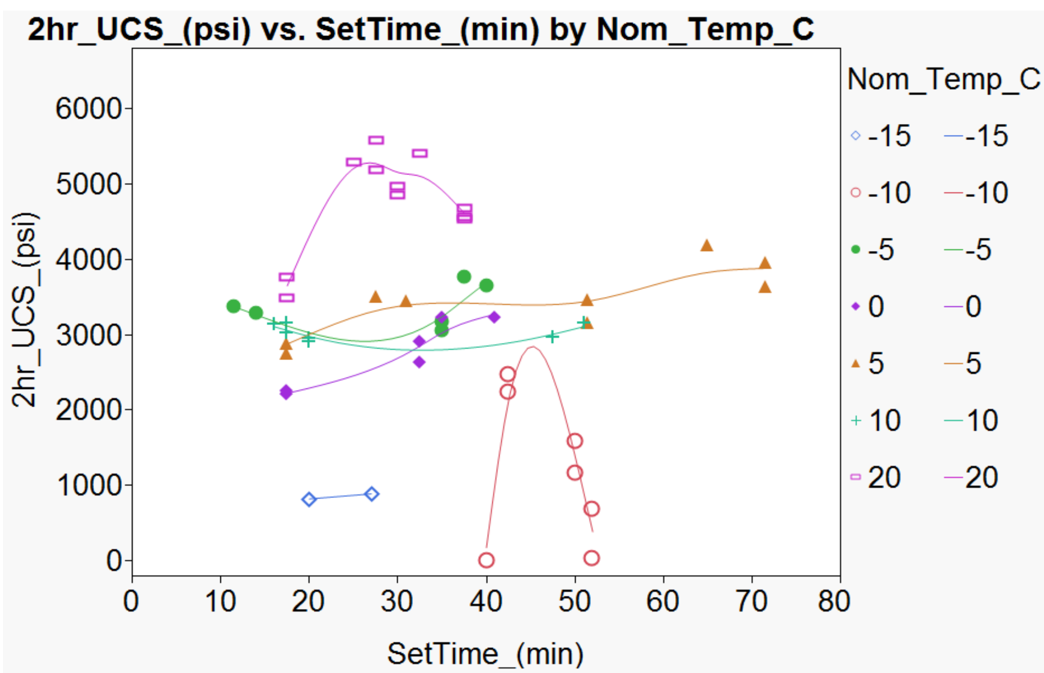
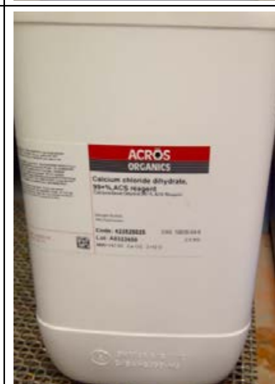
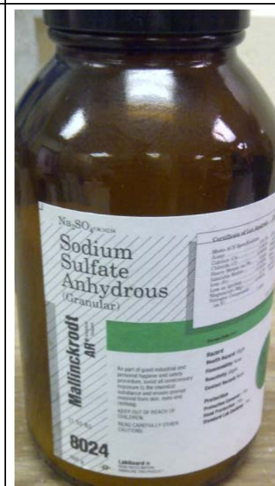


Figure B6. Task 3 (aluminum sulfate) testing: 2 hr UCS vs. set time (time to reach 500 psi, in min), filtered by testing temperature (°C). All completed tests in task 3 are shown.

Appendix C: Materials

Item	Chemical Formula	Manufacturer	Unit	Cost ($)/ Unit	Description / Notes	Photo
Aluminum Sulfate (hydrate)	Al2S3O12.xH2O; x = 12–14	Fisher Scientific	3 kg	66	purchase from GSA catalog; strong accelerator	
Calcium Chloride (dihydrate)	$CaCl_2$	Acros Organics	2.5 kg	234	99%+ pure; pellet form; any manufacturer ok if pellet, ~95% pure; accelerator and freezing point depressant	
Calcium Nitrate (fertilizer)	$Ca(NO_3)_2$	Yara Liva	22.7 kg	25	15.5-0-0 formula: 15.5% total nitrogen, 19% calcium; accelerator and freezing point depressant	

Item	Chemical Formula	Manufacturer	Unit	Cost ($)/ Unit	Description / Notes	Photo
Calcium Sulfate (hemi-hydrate)	$CaSO_4 \cdot .5H_2O$	Fisher Scientific	10 kg	348	aka calcined gypsum or plaster of Paris; potential accelerator	
Cane Sugar (granulated)	$C_{12}H_{22}O_{11}$	C&H	2.3 kg	5	sucrose; temporary retardant	
Glenium 7500 water-reducer	unknown (COTS product)	BASF	1 kg	2	COTS high-range water-reducing admixture	
Pozzutec 20+ accelerator	unknown (COTS product)	BASF	15.3 kg	Unk	COTS non-chloride, water-reducing and accelerating admixture	
Rapid Set Concrete Mix	COTS (Exact contents/ proportions unknown)	CTS	—	—	Approximate ratios: 1:1.1:1.1 type III cement:sand: crushed stone; additional accelerators and other contents may be present	

Item	Chemical Formula	Manufacturer	Unit	Cost ($)/ Unit	Description / Notes	Photo
Sodium Nitrate	$NaNO_2$	Dudadiesel Biodiesel Supply	2.3 kg	13	99.2%+ pure prills (pellets); potential accelerator	
Sodium Sulfate (anhydrous)	Na_2SO_4	Mallinckrodt	.5 kg	6	potential accelerator	
Utility Fill	COTS (Exact contents/ proportions unknown)	CTS	—	—	"flowable fill;" approximate proportions: 93% sand, 7% type III cement (with possible admixtures)	

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The Airfield Damage Repair Modernization Program

14. ABSTRACT

The research included in this report investigates admixtures that can improve the low-temperature early strength gain performance of two products already in existence (which are currently in limited use by the Air Force) for hasty runway repair. The first product, a "flowable fill," is a low-level cementitious sandy mixture used to rapidly fill the bulk of a runway crater; the second product, a rapid setting concrete, seals the final 10–12 in. of the crater and allows heavy-vehicle trafficability.

The primary operational requirements, which the current two-part solution meet at higher temperatures (greater than 10°C) but which require improvements at lower temperatures (−10°C to 10°C), involve time of set and 2 hr unconfined compressive strength (UCS). This research ignores typical concerns, such as long-term durability, aesthetics, and corrosion, that are of minimal importance in this expedient field-use application—horizontal surface repairs not expected to last more than two to five years. Results from this study are expected to be incorporated into operational testing, using Air Force equipment, personnel, and techniques, for small and large crater repair at sub-freezing temperatures. This report describes laboratory tests to improve the early strength gain performance of both repair materials to repair small-to-large craters at ambient temperatures of −10°C to 10°C.

15. SUBJECT TERMS

Airfield damage repair	Crater repair	Runway repair
Cold weather concrete	Flowable fill	
	Rapid set	

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